
EFFECTS OF SURFACE
DISTURBANCE ON PERMAFROST

SOME EFFECTS OF SURFACE DISTURBANCE ON THE PERMAFROST ACTIVE LAYER AT INUVIK N.W.T.

by

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1. Summary

Work has been undertaken at Inuvik, N.W.T. since May 1969, investigating selected disturbances to determine their effects on the permafrost active layer. Disturbances considered have been forest fires, removal of trees and removal of surface vegetation and soil. Results observed to date suggest that forest fire, of itself, is not a serious disturber of the permafrost environment. The main effect is a thickening of the active layer and an increase in the incidence of slope failure. Removal of trees, without mechanical damage of the ground flora, does not have any marked effect. Stripping of surface vegetation and soil have immediate serious effects. On level sites the active layer thickens, the ground surface subsides and hummocks collapse. Revegetation is slow. On slopes these effects are complicated by the movement of water from melting of permafrost and severe erosion can occur. The degree of seriousness of these effects is partly related to the season of the year. Summer disturbance is more serious than winter disturbance.

2. Introduction

Part of the Geological Survey's continuing programme is the provision of geologic and geomorphologic information on northern terrain, as a basis for the sound and rational management of the Canadian north. A significant factor in all studies of northern terrain is the perennially frozen nature of the ground - the permafrost - together with the thin upper layer of the ground that thaws each summer and freezes each winter - the active layer. Permafrost is reported to underlie about half of Canada (Brown, 1970), and consequently studies of the behaviour and properties of frozen ground material are just as important as studies of unfrozen materials in other parts of the world.

The study to be described here is a continuing investigation of the permafrost active layer in the forest-tundra environment in the area around Inuvik, N.W.T. (Figure 1).

The specific objectives of the projects involved are to investigate the nature of the active layer and to study its response in differing situations to various types of disturbance, both from natural and man-induced causes, and to identify and determine the importance of the environmental factors that control the performance of the active layer.

Information derived from this work is being used in the development of mapping systems to portray terrain sensitivity, that is, the performance or sensitivity of various terrain units in response to the activities of man. The information will also be of use in the production of guidelines and regulations to minimize some of the less desirable effects of land use and northern development.

3. Résumé of current knowledge

A search through the scientific literature concerning the relation between man and permafrost terrain reveals that while a fair amount of material on the effects of the terrain on man has been published, much less has been written on the effects of man on the terrain. Furthermore most of the reports concerned with the results of man's efforts have been published within the last four or five years. Indeed, the bulk of the literature references to permafrost are relatively recent, and there are few references to permafrost or perennially frozen ground from before the Second World War.

The general history of permafrost investigations, including some comments on the results of ground surface disturbance and the removal of the vegetation mat are summarized by Legget (1966) and Brown (1970). Several studies concerning the effects of terrain disturbance have been published recently (Brown, Rickard and Vietor, 1969; Hok, 1969; Kallio and Rieger, 1969; Kevan, 1971; Mackay, 1970; Watmore, 1969); a useful bibliography that cites a number of other pertinent reports has been published by the Forest Management Research Institute, Department of the Environment (Roberts-Pichette, 1972); other pertinent reports may be found in the Proceedings of the Permafrost International Conference (NAS-NRC, 1966), in the Proceedings of the Canadian Northern Pipeline Research Conference (Legget and MacFarlane, 1972), in the Proceedings of the Fire in the Northern Environment Symposium (Slaughter, Barney and Hansen, 1971) and in the Bibliography of Cold Regions Science and Technology (USA-CRREL, 1951 to date). Finally, mention must be made of the series of reports being produced under the sponsorship of the Arctic Land Use Research Programme of the Department of Indian and Northern Affairs. Several of these, especially those by Kerfoot (1970, 1972a), are concerned with the effects of terrain disturbance on permafrost and the active layer. Details of the reports published to date are given by Roberts-Pichette (1972). A selected, annotated bibliography of the effects of surface disturbance is presented in Appendix A.

Examination of the pertinent literature suggests certain conclusions with regard to the effects of engineering activities and development in permafrost terrain.

1. Fine-grained soils are apparently normally wet (or have a high ice content) and they are therefore subject to severe reaction if the insulating layer of surface vegetation is broken or badly damaged. On level sites, this reaction will normally be in the form of thermokarst subsidence; on slopes it will normally include thermal erosion and/or more or less severe slope failure.

2. Coarser grained soils are apparently normally fairly dry (or have a lower ice content) and do not usually react much to disturbance. However, visible scars, resulting from disturbance, can persist for many years or decades.

3. One potential problem appears to be due to the alteration, ponding or concentration of surface drainage. This can easily lead to changes in the soil thermal regime, melting of permafrost and subsequent erosion or subsidence.

4. Recovery or stabilization of areas which have reacted to disturbance promises to be generally slow and frequently unsatisfactory. Visible scars will remain for long periods of time.

5. Much more work needs to be done in certain areas; in particular, with regard to prediction of the water-ice content of the ground and with regard to rehabilitation measures.

4. The Study Area

The work being reported here has been undertaken in the area of Inuvik, N.W.T., Canada (Figure 1). Intensive studies of disturbed areas and studies of controlled disturbance have been undertaken close to Inuvik townsite, and less detailed studies have been done at several abandoned oil well sites around the head of the delta.

The general geology and geography of the Mackenzie Delta area is described by Mackay (1963), with some more up-to-date information provided by Fyles, Heginbottom and Rampton (1972), Hughes (1972) and Kerfoot (1972b). Of the eight abandoned oil well sites visited, six are on the Peel and Anderson Plains (Bostock, 1970), one of the others is near the northern end of the Peel Plateau, while the eighth is on an alluvial fan between Richardson Mountains and the Mackenzie Delta. The town of Inuvik is situated on a kame terrace deposit, between the south end of the Caribou Hills and the Mackenzie Delta (Fyles, Heginbottom and Rampton, 1972). The detailed studies have been undertaken in a variety of sites. All are areas of fairly thin, clay-silt till, derived largely from the broad expanse of Cretaceous shales to the east. This till variously overlies Palaeozoic dolomites, or Cretaceous shales. Some study sites are on low-angle alluvial fans, which are formed of a clay-silt derived from the till, and built on Pleistocene, kame terrace gravels. In all cases the subsurface material is rendered impervious by being frozen to depths of more than 100 m.

The structure of the active layer in this area is of some interest. The most obvious feature of the ground surface in the Inuvik area is its hummocky nature. The upper layer of the ground is a complex of mineral soil hummocks separated by shallow, moss-filled trenches. The hummocks are composed of a dense, grey-brown clay-silt, showing little or no soil profile development. In undisturbed areas, some hummocks have mineral soil exposed at the surface, but most are covered with a thin layer (less than 5 cm) of humus, mosses and lichens. The hummocks are roughly equidimensional on level sites, and generally one to two metres across. On the steeper slopes, they are elongate downslope, and narrower. The trenches between the hummocks are between 30 and 80 cm wide and about 35 cm deep. The trenches are moss-filled, commonly with bog-moss (Sphagnum), and are underlain by tapering masses or stringers of peat that extend well below the base of the natural active layer.

5. Methods, sources of data and results

5.1 Two main approaches have been used in this study. One is the examination of sites which have been disturbed in one way or another at known times in the recent past, to see what effects the disturbance has had on the terrain and the active layer. The other is the observation of developments following controlled disturbance of selected natural sites. Work began in 1969, with emphasis on the first approach, and with special reference to the forest fire of August 1968 at Inuvik.

5.2 Case histories of previously disturbed sites. In studying previously disturbed sites, the factors that are considered may be grouped into (i) those describing the activity, its nature, and its intensity; and (ii) those describing the terrain before and after the activity, and thus the effects of the activity on the terrain. As in many other environmental studies it is necessary to substitute a space variable for the time variable. The details of the terrain before the disturbance are considered to be essentially identical with details of the terrain immediately beyond the area affected by the disturbance.

In the area around the southern Mackenzie Delta, there are three broad groups of activities which can cause terrain disturbance. These comprise settlements and related activities, forest fires, and oil and gas exploration activities. To date only disturbances resulting from forest fires and oil and gas exploration have been examined. Settlements as such have been excluded from study because the actual activities associated with an observed effect are frequently unknown, and the occupation of the settlement sites has extended over relatively long periods of time (over 130 years at Fort McPherson). Thus several of the factors to be considered in the study of a disturbed site cannot be identified or described.

5.2.1 Forest fire. Forest fires present disturbance of a known type, over a fairly well defined area and normally with quite well known start and finish times, at least for the more recent fires. Older fires are less well documented and the record is incomplete. The locations of the known large forest fires which have occurred since 1960 are shown on the map (Fig. 1). For this study, 'large fires' are fires whose final areal extent was 10 acres (4 ha) or larger.

Detailed studies of the effects of forest fire on the active layer have been concentrated on the 1968 fire around Inuvik. Associated with the disturbance of the forest fires themselves, are the effects of the fire fighting activities. These normally take the form of fire-breaks cut by hand or with bulldozers. In the case of the 1968 Inuvik fire, bulldozers were used widely and some 25 miles of fire-break were constructed (Hill, 1969). The primary method of studying the effects of the fire and the fire-break has been precise levelling of the ground surface elevation and by measuring the thickness of thawed ground with a thin steel probe. An experiment was designed to fulfil this: in 1969 four 100 ft. (30 m) lines were laid out and the ground surface elevation measured, relative to an available bench mark, at one foot (30 cm) intervals. These lines have been re-surveyed, at the same stations, twice each year since, except for the fall of 1970. The details of the survey procedure are described elsewhere (Appendix B), and the data are summarized in Table I. Figure 2 presents a series of frequency distribution diagrams of the depth of thaw on the various survey dates, and it may be seen that most of the

Table I: Summary of depth of thaw measurements from the site of the 1968 forest fire near Inuvik[a)]

Terrain type	Undisturbed	Burned	Bulldozed
Date of survey b)	18 Sept. 1969	16 Sept. 1969	17 Sept. 1969
Surface elevation c)	243	521	428
Depth of thaw d)	0 - 43 - 75+	18 - 42 - 75+	38 - 65 - 75+
Date of survey	18 Sept. 1971	17 Sept. 1971	18 Sept. 1971
Surface elevation	237	507	407
Depth of thaw	21 - 42 - 77	25 - 55 - 100	38 - 100 - 138
Date of survey	14 Sept. 1972	15 Sept. 1972	14 Sept. 1972
Surface elevation	223	495	399
Depth of thaw	25 - 48 - 85	31 - 61 - 110	72 - 120 - 140 (estimated from partial sample)

Notes: a. The forest fire and the fire fighting (bulldozing of fire-breaks) occurred in August 1968.

b. Only fall survey data are shown, as these represent the annual maximum depth of thaw and are thus a measure of the thickness of the active layer.

c. The elevations given are mean elevations, rounded to the nearest centimetre and based on an arbitrary bench mark elevation.

c. The depths given are minimum - median - maximum values, also in centimetres.

distributions are far from normal. There are three main forms of distribution: unimodal, bimodal and complex. Examples of unimodal plots are all three lines for spring of 1969 and 1972 and line A2 on several other occasions. Bimodal distributions include line B1 for fall 1969, fall 1971 and fall 1972 while good examples of complex distributions include line A2 for fall 1971 and fall 1972.

These three forms of distribution are related to a) date of survey, b) microtopography and c) severity of surface disturbance. The unimodal distributions of spring 1969 and spring 1972 result from surveys done early in the thaw season. The bimodal distributions result mainly from the difference in thaw depths that occur under mineral soil hummocks and under the peat masses between hummocks. Line B1 for 4 July, 1970 is a particularly good example of this, for the median depth of thaw was 48 cm in hummocks of mineral soil, while in the peat it was only 17 cm. These values are very close to the peaks in the distribution curve. Curves with complex frequency distributions are chiefly related to line A2, the bulldozed fire-break terrain. Here the pattern of peat and mineral soil was more or less completely destroyed by the bulldozing, and the depth of thaw histogram reflects the disturbed nature of the active layer here.

To summarize, the effects of the fire and of the bulldozing of fire-breaks are similar - the ground thaws more deeply in summer due to the destruction or removal of the insulating blanket of peat and cryptogams. This deeper thawing allows some of the high ice-content ground below the active layer to melt and, as this meltwater drains out of the soil mass, the ground subsides. Calculations of the volume of ground lost due to drainage of meltwater suggest that the upper metre of the ground contained about 33 per cent by volume excess ice before disturbance. The data presented in Table I shows the greatly increased depth of thawing in the area that was bulldozed, compared to the area that was burned.

In 1972 incidental observations were made at the site of a 1954 tundra fire area south of Old Man Lake. This area was visited and described by Cody in 1957 and 1963 (Cody, 1964). At the location visited in 1972, the terrain had not been severely altered as a result of the fire. Many plants were making a good comeback, with the exception of the cryptogams and black spruce. The depth of thaw was between 15 and 25 cm. No erosion or slope failures were seen.

Other observations in 1969 in the area of the 1968 fire at Inuvik disclosed the presence of a number of fresh slope failures of the type referred to by Hughes (1972) as active layer "detachment failures". These have been discussed elsewhere (Appendix B) and will not be described further.

5.2.2 <u>Oil and gas exploration</u>. Oil and gas exploration activities have been widespread in the study area for over a decade. The activities have taken the form of surface seismic profiling, followed by the drilling of wildcat wells. Sixteen oil wells are shown on the map (Fig. 1); the oldest was completed in 1960, while two are still drilling at the time of writing (October, 1972). The trails left by the seismic profiling teams are so numerous and widespread that no attempt has been made to map them here.

During the summer of 1972, brief visits were paid to eight of the ten oil well sites in the south half of the area mapped in Fig. 1. Of the remaining well sites, one was flooded and the other was still occupied by the drill rig. Most of these oil well sites had a similar layout, in the form of a rectangle of land from which the trees had been cleared by bulldozer. These "squares" were generally about 120 to 150 m on a side. Running through or beside the square were one or more seismic trails, and a trail leading from the square to either a temporary airstrip or to a lake or river on which planes could have landed. The actual well-head was near the centre of the square with the slush pit beside it and the remainder of the camp facilities around them. The sites were occupied for periods varying between three and seven months, mainly during the winter. The actual sites visited are listed and briefly described in Table II. At each site the observations made covered variations in depth, apparent intensity and type of original disturbance, notes on the original terrain and the present conditions, variations in the depth of thaw and amount of regeneration. Details of the surficial geology are being derived from seismic profile shot-hole drilling logs, but are not available yet.

The effects of the oil rig and well drilling activities are difficult to assess. Right around the well-head area, gravel and/or woodchips are frequently spread as an insulating blanket. Woodchips are particularly effective at this if spread fairly thickly. At Attoe Lake I-06, on 20 June 1972, the ground was thawed for only 10 cm below a 25 cm thick layer of woodchips, compared with 60 cm under a burned hummock outside the rig square. In general the depth of thaw was deepest close to the well-head and became less towards the edges of the square. This is what one would expect, in view of the concentration of activity and of destruction of the vegetation mat in the centre of the area.

Cleared airstrips were examined at three sites. At Attoe Lake the airstrip was formed by just bulldozing the trees and topmost level of moss off an area of fen, leaving an insulating layer of peat. The airstrip at Shell Tree River was similarly made, and was situated on a terrace of glaciofluvial gravels, with a cover of peat. This airstrip exhibited the widest variation in depth of thaw of the three examined. The third airstrip was on one of the alluvial fans, west of the Delta. The surface of the centre of the airstrip was under about 15 cm of water, while both ends were waterlogged but not flooded. Sample profiles across these airstrips are shown in Figure 3.

Access roads and seismic trails may conveniently be considered together, as their nature is very similar. Numerous examples of each were examined around the eight oil well sites visited. Sample profiles across six seismic lines are presented in Figure 4. The range of conditions seen on the seismic lines and trails was very wide. Apparently the critical factor controlling the amount of change subsequent to the initial activity is the manner in which the trail was cut. If the trail was cut in summer by bulldozing the trees and the surface vegetation mat aside, then subsequent thawing of the ground proceeds for several years. The effects are the same as those described under the discussion on fire-breaks. This is illustrated in Profile D at Swan Lake (Fig. 4a) where a strip down the centre of the trail was cleared by bulldozing. This strip has sunk somewhat and the ground is thawed relatively deeply and is completely saturated above the frozen layer. The strips on the sides were cleared of trees, but the vegetation mat was largely undisturbed. The surface

Well Name	Location	Drilling Date	Numbers and types of features examined					Nature of other features	Surficial Geology (See Note)
			Rig Site	Air-strips	Access Roads	Seismic Trails	Other		
INC - NCO - Mobil Attoe Lake I-06	67°25'N 133°15'W	July 69 - Dec. 69	1	1	3	3	No		Till plain and fen
IOE Tree River H-38	67°17'N 132°21'W	Mar. 67 - Apr. 67	1	0	1	2	No		Peat over glacio-lacustrine deposits
Shell Tree River F-57	67°06'N 132°26'W	Nov. 67 - Dec. 67	1	1	1	2	Yes	Borrow pit and river crossing site	Peat over outwash gravels
Shell Tree River East H-57	67°06'N 132°26'W		1	0	0	1	No		Peat over glacio-lacustrine deposits
IOE Swan Lake K-28	67°08'N 133°35'W	Jan. 67 - Mar. 67	1	0	1	2	No		Till Plain
IOE Stoney I-50	67°30'N 135°23'W	Dec. 65 - May 66	1	0	6	4	Yes	Campsites and staging areas	Till plain with thermokarst
Banff-Aquit-ARCO Treeless Creek I-51	67°51'N 135°24'W	Dec. 70 - Jan. 71	1	1	1	1	Yes	Campsite	Alluvial fan
Richfield *et al.* Point Separation No. 1	67°34'N 134°00'W	July 60 - Oct. 60	1	0	1	1	Yes	Campsite	Till plain

Note: Surficial geology is after Hughes, Hodgson & Pilon, 1972.

Table II: Details of Oil well sites and seismic trails examined, summer 1972.

is much drier and the depth of thaw is less; in fact it is very similar to conditions in undisturbed areas. Profile E at Swan Lake (Fig. 4b) refers to a newer seismic line which crosses the one just described - both profiles were taken 30 m from the intersection. This line was constructed by having the bulldozer knock down and push aside only the trees. The only disturbance of the vegetation mat was a few grouser marks. As the profile suggests, conditions in the trail were essentially similar to those off to the side. The contrast between two seismic trails is further illustrated in Fig. 5. Most of the trails examined were in fairly good condition, and no really severe thermokarst effects were seen. Vegetation regeneration on bulldozed trails appears to be slow.

The other features seen at the oil well sites comprised four campsite or staging areas, a borrow pit and a river crossing site. The campsite areas were similar to oil rig sites in most respects. At the borrow pit it was difficult to interpret how much change had occurred since it was abandoned. The material was coarse, rounded, outwash gravels and very possibly there has been little or no change. The trail from the borrow pit to the rig site showed an interesting example of erosion being guided by vehicle track marks (Fig. 6).

5.3 Controlled disturbance of sites. The second approach used in this study has been the observation of developments following deliberate, controlled disturbance of selected natural sites. This work is still in progress, and at this time only preliminary observations can be made. This detailed work is being done close to Inuvik for logistical reasons. The work began in 1970 with the selection of three sites and, at that time, access trails to the sites were cleared and deep pipe bench marks installed. The sites selected are described briefly in Table III.

5.3.1 At each site, the layout of the plots was similar. Six squares 10 m on the side were laid out along the contour of the slope, with 5 m buffer zones between the squares. These squares constituted the test plots. A broad access trail was cleared along the down-slope side of the rows of plots. In each case the plot farthest from the entrance was designated the control plot. These plots have remained undisturbed except for the annual survey. The next plots were undisturbed, except for the removal of the tree and shrub vegetation, which was done by hand. The remaining plots were disturbed by stripping off the "topsoil" with a bulldozer. For technical reasons this was done in winter time. Of the four plots at each site that were bulldozed, two were bulldozed fairly deeply, and the others to a shallower depth. The effects of their disturbance have been monitored in three ways - by survey on the ground surface, by installing shallow temperature cables and by installing shallow piezometers.

The surveying has been done with a level and staff, using deep pipe bench marks as the origins, and a chain grid to determine the survey stations. The points are arranged in a regular 71 cm grid. The depth of thawed ground is measured with a steel probe. Two surveys have been undertaken, in August of 1971 and in August of 1972. The data from 1972 have not been processed at this time, and so statistical comparisons cannot be made yet.

In two bulldozed plots at MS 1 and MS 2, eight shallow ground temperature cables were installed in the summer of 1971. Each cable contained four thermistor beads. The cables were lowered into holes made with a portable earth drill, the thermistor beads being placed at depths of 25, 50, 100 and 200 cm from the ground surface. The holes were located either side of the edge of

Table III: Details of Manipulation Sites, Inuvik, N.W.T.

Site No.	Slope	Aspect	Soil Material	Micromorphology	Vegetation
MS 1	3.5°	South	Clay-silt till and organic	Hummocky	Open spruce-lichen
MS 2	3.5°	North	Clay-silt till and organic	Hummocky	Open spruce - lichen
MS 3	6°	North-west	Clay-silt till and organic	Hummocky	Spruce-willow-lichen

a bulldozed plot in a layout that would permit comparison of bulldozed with unbulldozed areas, and south with north aspect, and would provide information on the lateral spread of the effects of bulldozing beyond the edge of the plots. The ground temperatures are measured each week with a precision Wheatstone bridge.

In September 1972, thirty-one shallow piezometers were installed in one of the bulldozed plots at Site 1. These were designed and installed by Dr. A. Lissey of Brock University, working under contract to the Geological Survey. The piezometers were grouped in three nests of ten each, plus a single piezometer. Each piezometer within a nest was screened at a different depth. The vertical distance between screens was set at 10 cm and the deepest piezometer in each nest was completed at a depth of 100 cm. One nest was located in the centre of a pre-existing mineral soil hummock, the other two within the organic material separating hummocks. The single peizometer was located in undisturbed terrain upslope of the bulldozed plot.

The purpose of these installations is to observe the quantities and movements of groundwater in the active layer, particularly during periods of freezing and thawing. The piezometers are being read on a weekly basis to monitor groundwater behaviour in the active layer throughout each season of the year. A more detailed report on the piezometers is to be submitted separately (Lissey 1973).

5.3.2 Finally, some detailed work is being done on the undisturbed active layer as a control on the disturbance studies. The various experiments noted above all have specific control surveys as part of their basic design. However four other shallow temperature cables have been installed in an undisturbed area near Inuvik. Two of the cables are in holes drilled into mineral soil hummocks, and two are in holes in the organic material separating the hummocks. Ground temperatures are being recorded quasi-continuously from two of these cables, while the other two are measured each week with the Wheatstone bridge.

Readings are available from all the temperature cables for over a year, and a preliminary evaluation of some of them has been presented elsewhere (Appendix C).

6. Discussion

For the purposes of discussion it is convenient to discard "agent" centred terms such as forest fire, oil exploration, bulldozing etc., and to replace them with "process" centred terms. Thus the activities and disturbances described in the preceding section may be termed: compaction of ground surface, mechanical damage to vegetation, destruction of vegetation, removal of vegetation, removal of vegetation-peat mat and removal of surface vegetation and soil. Using terms such as these, one is in a position to compare the effects of diverse activities and agents of disturbance. Furthermore, the processes listed above are parts of a continuum which ranges from the very mildest of disturbance (a single man walking through the forest once) to very severe disturbance (repeated deep bulldozing and soil stripping). As the processes are parts of a continuum, so their effects are, and this is also a convenient framework for discussion. Rankings of agents, processes and severity are presented in Table IV in terms of the intensity of the initial impact.

The general effect of this continuum of processes may be summarized thus: any compaction alters the thermal transfer properties of the soil material, and any removal of surface vegetation alters the albedo. In most cases both these changes lead to an increase in the downward flux of heat in summer, and thus to deeper thawing of the ground and a thicker active layer. Mackay has commented that "The top several feet of the permafrost tends to be an ice-rich zone which is easily affected by a surface disturbance" (Mackay, 1971) and in the same paper he outlines an explanation of this observation. When the active layer thaws more deeply following surface disturbance, it is this ice-rich zone which melts first, and if the excess water is able to drain away, there is a permanent subsidence of the ground surface (Appendix B; Mackay, 1970). It must be pointed out that this sequence of events only occurs in "frost susceptible soils", i.e., in fine-grained soils. Granular soils, such as sands and gravels do not react by subsiding as there is not usually any excess ice in such soils: deeper thaw following disturbance is the extent of the effect of a thickened active layer.

On sloping sites other changes can happen in both fine-and coarse-grained materials. These take the form of slope failures, mass movement and landslides of various kinds. Mention has already been made of the earth-flows which occurred after the 1968 fire in Inuvik. Other comments on slope failure following disturbance are given by Isaacs and Code (1972), while Figure 7 shows a slope failure in the Inuvik gravel pit, following gravel extraction.

Most of the field work described in the previous section has been on level sites or on sites with low angles of slope, and the work was designed to consider a range of intensities of terrain disturbance, as outlined in Table IV. Not all agents and intensities listed in the table have been studied as yet. Thus no measurements have been made of the effects of minor amounts of compaction such as are produced by varying intensities of foot traffic. Two small examples of the effects of such disturbance are given by Mackay (1970). and related work from non-permafrost areas has been reported (Watson, Bayfield and Moyes, 1970). If the various National Parks and Landmarks proposed in permafrost areas of Canada become popular, measurements of disturbance due to foot traffic may be of considerable importance.

Removal of vegetation without any significant compaction can best be accomplished by hand. Such is the case in three of the manipulation plots

Table IV. Ranking of disturbing agents and processes in terms of the intensity of their initial impact.

Intensity	Agent	Process
Least intensive	Single to few passes of man on foot	Minor compaction
	Removal of trees by hand	Minor vegetation removal
	Single to few passes of vehicle (with minimal removal of vegetation)	Minor to medium compaction, minor mechanical damage and minor vegetation removal
	Forest fire	Vegetation destruction
	Multiple passes of man on foot	Medium compaction and minor mechanical damage
	Shallow bulldozing	Vegetation and soil removal, compaction
	Multiple passes of vehicles	Severe compaction, vegetation removal, and severe mechanical damage
Most intensive	Deep bulldozing	Severe vegetation and soil removal, compaction

Note: Agents not ranked because data are inadequate or agent impact is too variable:

Campsites and oilwells
Alterations of surface and near-surface drainage

described above and in Table III. Preliminary results suggest that the effects of such disturbance are negligible and possibly undetectable. Minor compaction with minimal vegetation removal as shown by the seismic trail illustrated in Figures 4b and 5a, or by air strips (Fig. 3) also produce negligible to minor effects.

The effects of mechanical damage to the surface vegetation mat are variable. If the albedo of the surface is sharply reduced, as happens if dark humus or peat is exposed at the surface in place of light coloured lichens and mosses, then deeper thawing takes place. If the mechanical damage is minor, and no colour change is involved, the effects are negligible. Severe mechanical damage, of which no examples were seen, will presumably result in a similar reaction to severe compaction or removal of surface vegetation.

Marked effects only appear with disturbances as severe as the more-or-less complete destruction of the vegetation, including the surface vegetation cover, which results from a forest fire. Such effects appear soon, within days in the case of a forest fire (Watmore, 1969), develop over several years (Table I) and persist for several more years (Cody, 1964). The actual time values for the periods of development and persistence are still under investigation.

The more intensive forms of disturbance associated with severe compaction, removal of all vegetation and removal of soil have been examined in several seismic trails (e.g. Figs. 4c-4f, and 5b). They are also under investigation in the manipulation experiments (Table III), where preliminary observations suggest that the more severe the original disturbance, the more rapidly the effects become apparent. The time required before stabilization or recovery occurs is not yet known.

Variation in the intensity of the original disturbance is not the only factor that controls the reaction of terrain to disturbance. The properties of the terrain itself are at least as important, and the time of year of disturbance and the time since the disturbance must also be considered. The properties of the terrain which control its reaction to disturbance comprise slope angle, aspect, soil material, vegetation and the moisture or ice content of the ground. The climatic cycle is important mainly in terms of whether or not the ground is frozen at the time of disturbance. Frozen ground is not normally subjected to compaction or to mechanical damage, and thus a higher intensity of activity will produce a lower intensity of disturbance than if the ground is unfrozen. The time since the disturbance is important only because many of the effects related to deeper thawing of the active layer take a number of years to develop.

The field observations of forest fires and oil and gas exploration sites provide some information on some of the terrain properties. However, the coverage is neither comprehensive nor detailed. The reason for this is simple - in studying existing cases of disturbance, one has to study them where they are. Particularly steep slopes or marshy areas are usually avoided and thus not represented. The detailed studies of controlled disturbance are designed to overcome some of these deficiencies in the other data. The three sites (Table III) cover north *versus* south aspect and two angles of slope (about 3° and 6°), and the shallow piezometers will provide some preliminary data on the relevant soil moisture conditions. Casual observations in the study area suggest that vegetation patterns are controlled in large part by differences in soil moisture or drainage, and by the forest fire history of the area.

7. Conclusions

Most of the sites studied, both in detail and casually, have certain features in common which control the effects of surface disturbance on the permafrost active layer. The sites are generally level or of low slope angle, thus minimizing effects due to slope angle *per se* and effects due to differing aspects. Most are on clay-silt till, with a hummocky surface and a more-or-less continuous mantle of peat, humus and living vegetation, dominated by cryptogams, and with relatively open stands of spruce, alder, birch and willow. Thus the one factor which overrides all others in controlling the effects of any terrain disturbance on the permafrost active layer at these sites is the intensity or severity of the original disturbance. Variations in the response of the terrain due to different original terrain conditions are much less. Variations on effects of disturbance with time of year can be regarded as being part of the intensity of the original disturbance.

8. Implications and recommendations

8.1 Intensity of initial impact: As suggested in the previous section, the observations reported here indicate that the intensity of the initial impact of any disturbance of the environment is of major importance in controlling the effects of that disturbance. Probably the best illustration of this is obtained by comparing the effects of carefully constructed airstrips (Fig. 3) with hurriedly bulldozed fire-breaks (Fig. 2). The former have had only negligible effects on the active layer whereas the latter have resulted in considerable subsidence and erosion.

8.2 Preservation of vegetation-peat ground cover: The high ice content of the uppermost levels of the permafrost has been highlighted by Mackay (1971); any thickening of the active layer leads to the melting of this high ice content material and hence to subsidence or slope failure. Obviously, therefore, every effort should be made to preserve the active layer in as undisturbed a state as possible. The best way to achieve this appears to be by preserving the integrity of the vegetation-peat ground cover.

8.3 Pipeline and highway construction: The nature of pipelines and highways is that of continuous, linear features. Their continuity has to be maintained, regardless of everything else, if they are to be effective. Thus in selecting a route for either a pipeline or a highway one may be forced to make compromises with regard to undesirable side effects in order to maintain continuity. Such compromises can be expected to include routes across areas of sensitive terrain, which, in the northern part of the Mackenzie Valley, includes areas of high ice content, fine-grained earth materials. In such areas pipeline or highway design must be such that the integrity of the vegetation-peat ground cover, and so of the active layer, is preserved.

8.4 Restoration of disturbed areas: Casual observation of a number of disturbed sites suggests that the measures for rehabilitation and restoration of disturbed areas, that are to be required of land use operations in the north, will need to be designed and undertaken with as much care and skill as all other phases of the operations. Thus in the case of the 1968 Inuvik forest fire, for example, the bulldozed fire-breaks have led to more serious changes in the terrain than has the forest fire itself (see Fig. 2). Similar opinions have been reported by other workers, and rehabilitative measures have been attempted (see various papers in Slaughter, Barney and Hansen, 1971). Some of the rehabilitative measures described should be considered for use by contractors and other land use operators in the Canadian north.

9. Areas requiring further study.

9.1 Continued observation of the effects of prior disturbance, and extension of this work to other forms of disturbance, to other geologic and topographic sites and to other levels of initial impact - both more and less severe. At selected sites this work should be supplemented by shallow drilling for soil samples from both within and outside the disturbed area. A subsidiary part of this work would be drilling for soil samples at some of the disturbed sites previously described and at the intensive study sites described in Table III.

9.2 Study of the effects of disturbance of the winter snowpack on the active layer and on the permafrost. Some work on the effects of snow roads has been done by Kerfoot (1972a), but no work on the effect of ice roads has been reported. Work from southern Canada and northeast United States on the effects of snowmobiles have shown that repeated passage of oversnow vehicles has led to the storage of more water at those points, increases in heat conduction through the snow pack and a time delay in the melting of the snow (Hogan, 1972; Neumann and Merriam, 1972). Hogan's work suggests that some of these effects may be beneficial.

9.3 Study of the effects of rehabilitative measures, both those that are planned as part of a construction project and those that have to be taken following unplanned emergency or accidental disturbances.

9.4 Shallow drilling for soil samples at some of the sites described in this report - primarily those close to Inuvik townsite.

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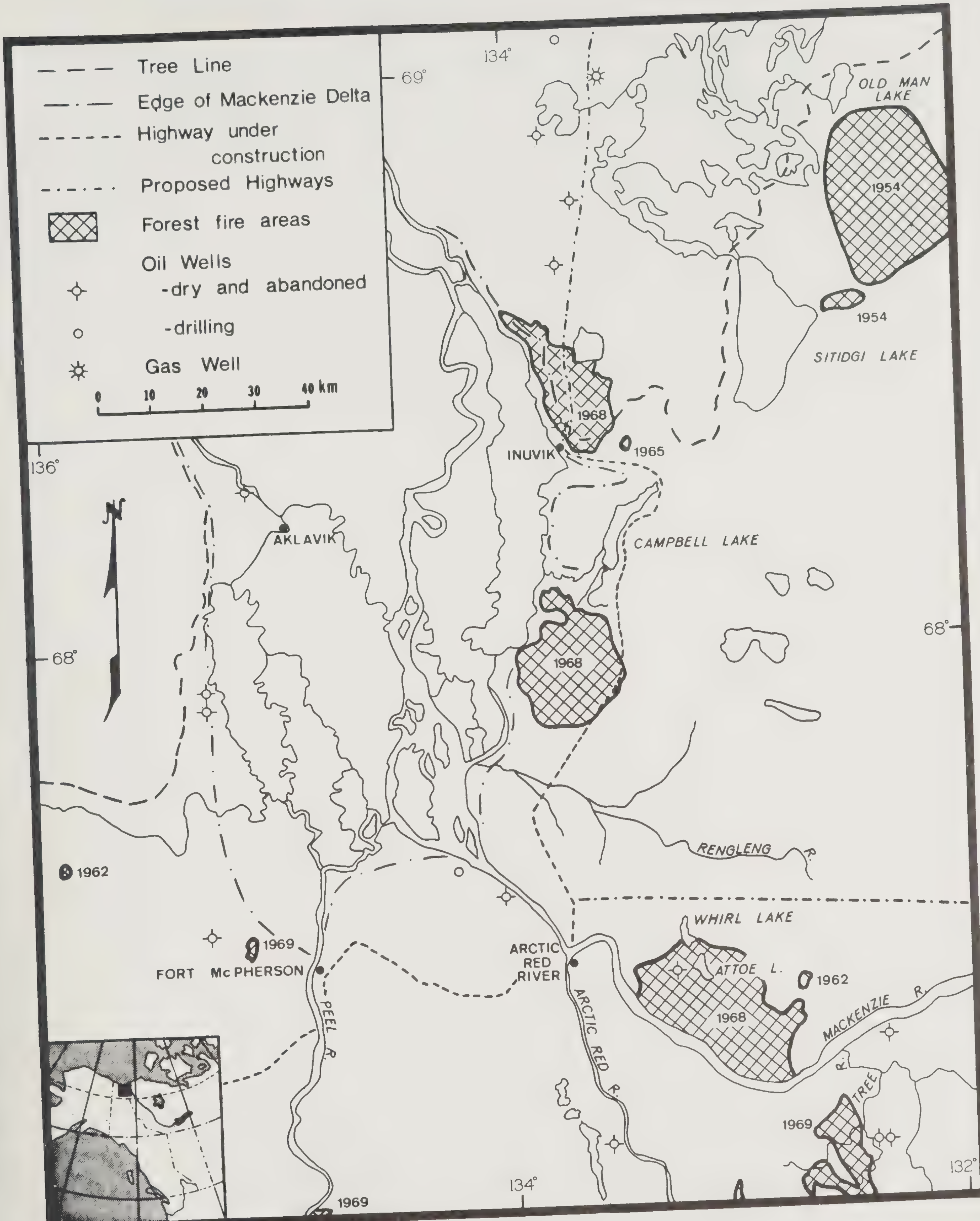

Figure 1: General location map of the study area: The Mackenzie Delta area, N.W.T., Canada.

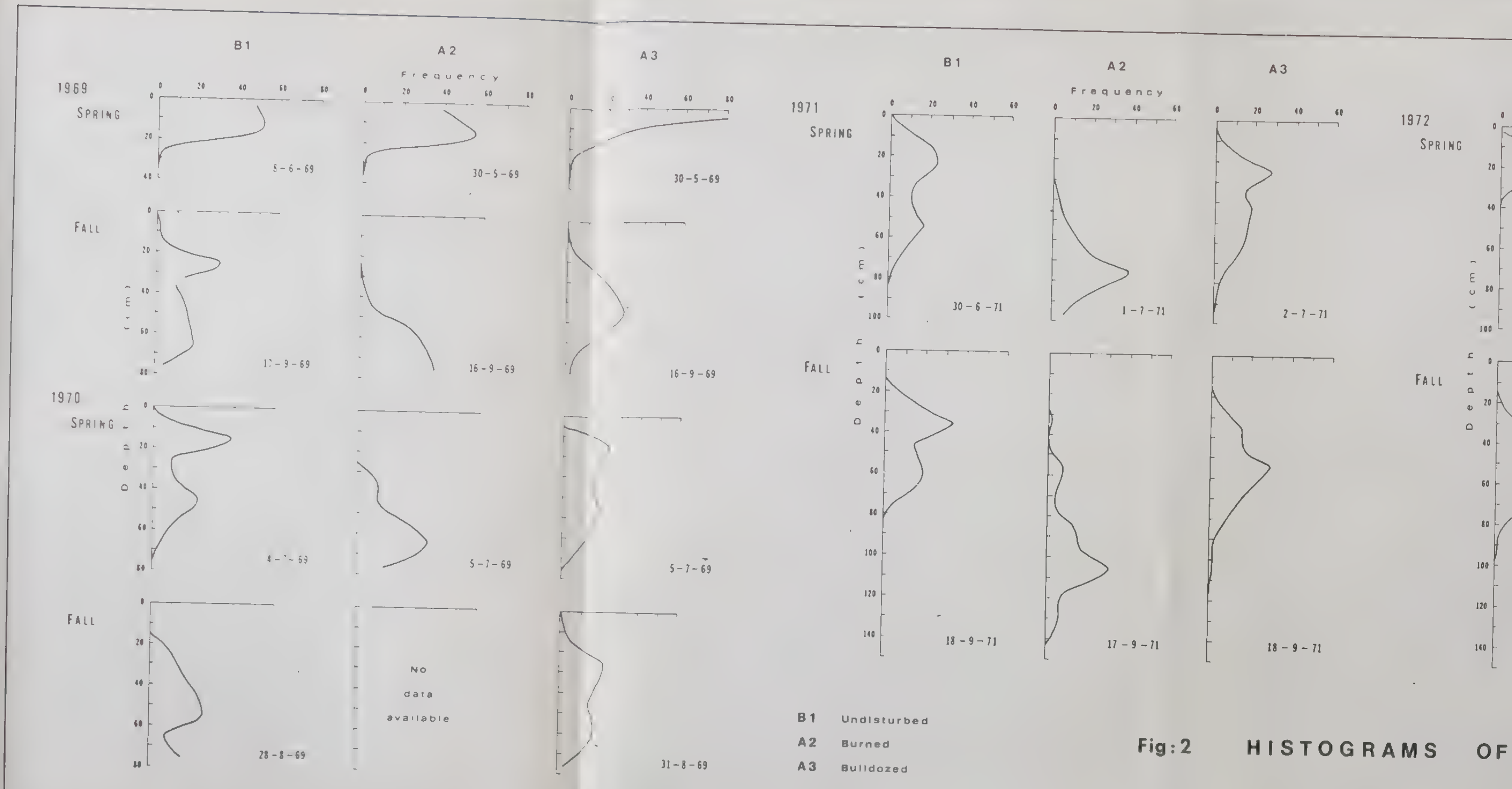

Fig: 2 HISTOGRAMS OF

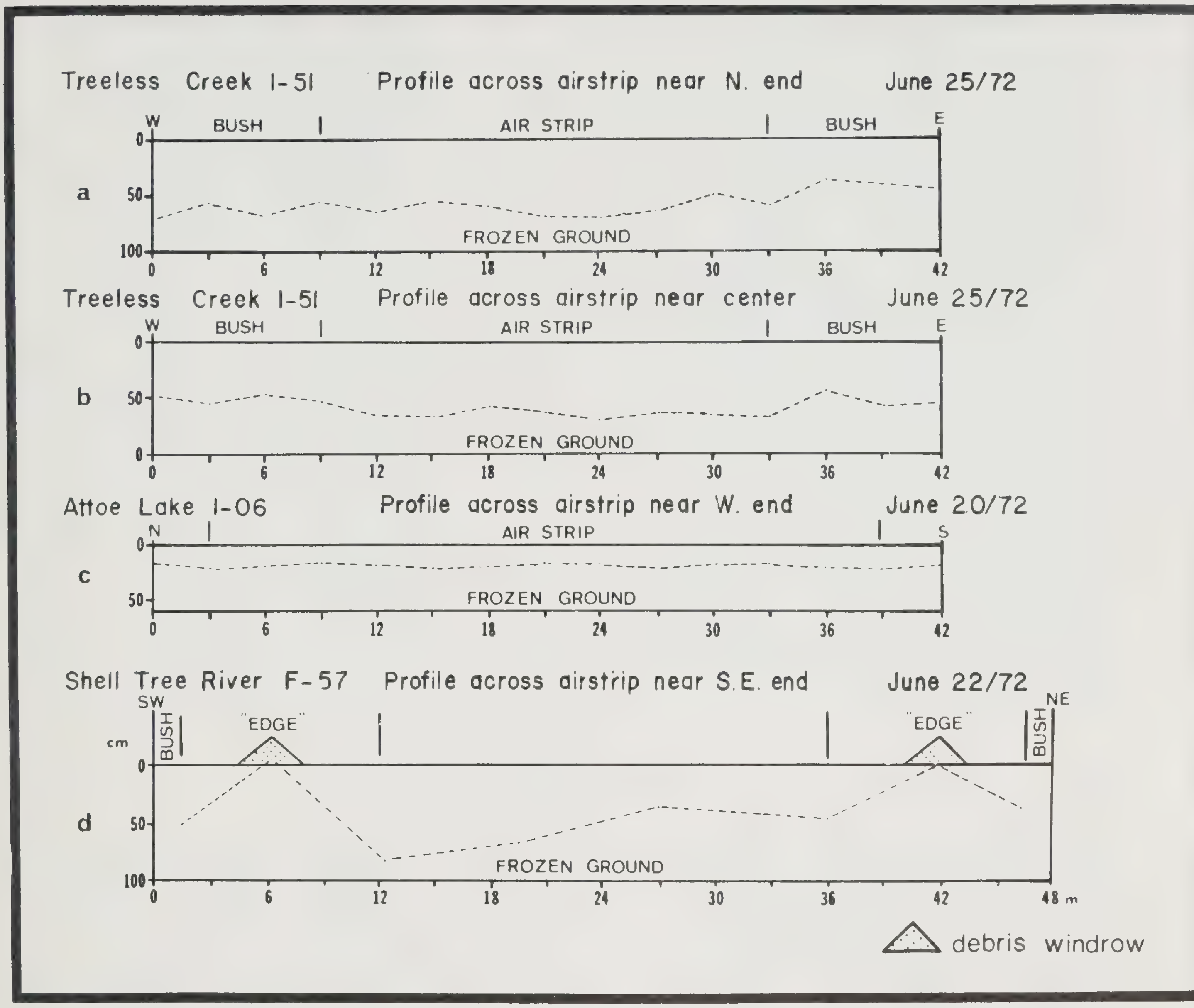

Figure 3: Profiles across disturbed areas: airstrips.

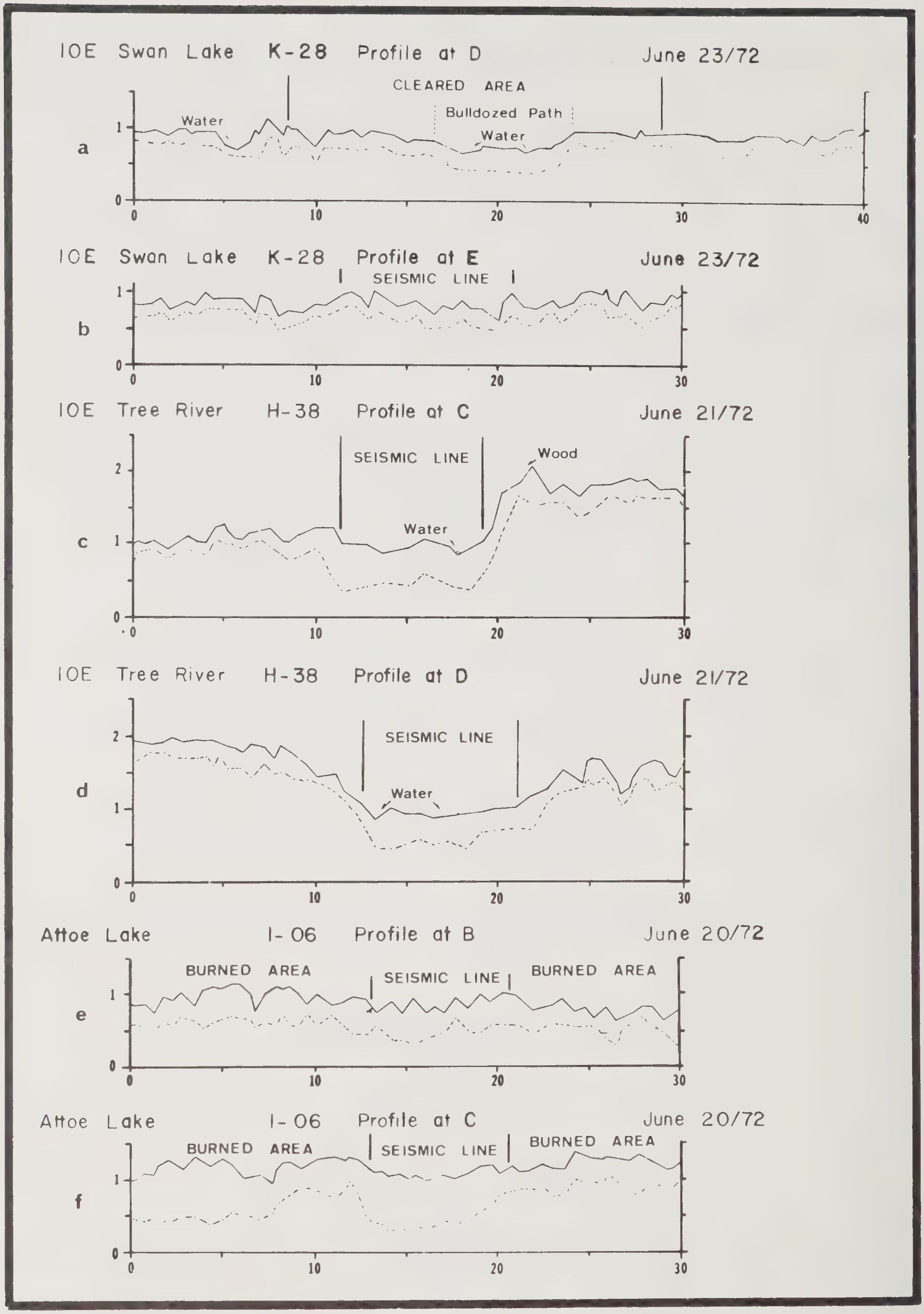

Figure 4: Profiles across disturbed areas: seismic trails.

Figure 5: Seismic trails near Swan Lake ($67^{\circ}08'$ N, $133^{\circ}35'$ W), 23 June 1972. Geological Survey of Canada photographs 202095-D, 202095-E.

Left: Recent trail with minimum of terrain disturbance.
Right: Old trail with bulldozed central zone.

Figure 6: Gullying being guided by vehicle track marks ($67^{\circ}06'$ N, $132^{\circ}26'$ W) 22 June 1972.
Geological Survey of Canada photograph 202095

Figure 7: Slump in gravels following excavation, Inuvik gravel pit, 27 July 1971.
Geological Survey of Canada photograph 202095-F

APPENDIX A

SELECTED ANNOTATED BIBLIOGRAPHY OF THE EFFECTS OF SURFACE DISTURBANCE ON PERMAFROST TERRAIN

This bibliography has been compiled largely by searching the libraries of the Geological Survey, Department of Energy, Mines and Resources, and the Division of Building Research. One visit was made to the library of the Defence Research Board, but as browsing was not permitted there, no further visits were made. Most reports cited by Roberts-Pichette (1972) have been deliberately omitted from this listing.

From the reading done to date, it is evident that few attempts have been made to study the effects of disturbance on permafrost terrain. There is a considerable amount of material describing the effects of permafrost on civil engineering projects. The problems encountered in Arctic construction and maintenance are well documented, but relatively little attention has been paid to changes in permafrost conditions following construction. In fact, very little was found describing the effects of disturbance on any type of terrain.

The main conclusion is that the only reports in the literature which are of real value to this project are those in which the author has set out to investigate, in some measure, the effects of disturbance on terrain conditions; the amount of incidental information in other reports is minimal.

The citations included are the more useful ones that were found. References to areas not analogous in some degree to the Mackenzie Valley - Arctic Coastal Plain areas were excluded.

Anon (n.d.)
1971 - North Slope Tundra Clean-up Group: Final Report. Atlantic Richfield Company. 24 p.

> p. 14: "The Rolligons occasionally left tracks that were visible.... Close examination revealed no damage to the tundra and inspection one month later disclosed that the tracks were rapidly disappearing. The Rolligons slightly compress the tundra, but do not break or tear it. The Rolligons averaged 3 to 4 miles per hour over average tundra surface. Extremely wet areas were avoided, in order to minimize unsightly tracking of the tundra."
>
> "In retrospect, the Rolligon proved to be a very successful summer operating vehicle, both environmentally & operationally."

Barnett, D.M. and Kuc, M. (1972)
Terrain performance, Melville Island, District of Franklin. Report of Activities, Part A, April to October 1971. Canada, Geological Survey, Paper 72-1, Pt. A: 137-139.

Preliminary conclusions indicate that even quite coarse-grained surface materials (several cm in diameter) are unsuitable for vehicular traffic at spring run-off. Conversely even the most susceptible fine-grained materials may dry out in summer to give a firm surface suitable for vehicles.

Where vehicular disturbance has led to particularly unstable conditions, such as at cut river banks, active gullying and slumping has resulted. These areas approach equilibrium conditions quite rapidly, consuming the tracks which triggered the process, and leaving a natural looking landscape. However where surface materials have been churned on a moderately stable environment, for example across a slope, then the process of natural reworking is somewhat longer term. The Winter Harbour examples indicate that the track-forms mute with time but that ten years later the tracks may still be visible and, in places, carry standing water.

Beschel, R.E. (1963)
Observations on the time factor in interactions of permafrost and vegetation. Proceedings of the First Canadian Conference on Permafrost, 17 and 18 April, 1962, Prepared by R.J.E. Brown, Technical Memorandum No. 76, Associate Committee on Soil and Snow Mechanics, National Research Council of Canada, Ottawa, pp. 43-56.

Following disturbances (p. 46-47), changes in permafrost may be very rapid. Removal of existing vegetation may cause development of thermokarst features. Rapid growth of plants occurs in the first year following removal of vegetation, probably due to increased moisture availability as permafrost thaws more deeply. Denser vegetation reduces runoff and distributes the water supply over a longer period of time. In later years, productivity decreases as the vegetation becomes re-established.

Bliss, L.C. and Wein, R.W. (1971)
Changes to the active layer caused by surface disturbance. Proceedings of a seminar on the permafrost active layer, 4 and 5 May, 1971 (ed.: R.J.E. Brown). Canada NRC/ACGR Tech. Memo No. 103: 37-47.

Summarizes data on increases in the thickness of the active layer following surface disturbances, mainly for north Alaska and the Mackenzie Delta area. Seismic lines (of various ages & cut at various times of the year) lead to an increase of about 75% while fires lead to increases of 30 to 50% in the maximum depth of annual thaw.

Bliss, L.C. and Wein, R.W. (1972)
Ecological problems associated with arctic oil and gas development. Proceedings, Canadian Northern Pipeline Research Conference, 2-4 February 1972 (ed. R.F. Legget and I.C. MacFarlane). Canada NRC/ACGR Tech. Memo 104: 65-77.

ABSTRACT

The Canadian Arctic covers 2.5 million km^2, about 23 percent of the country. In this vast area there are great differences in topography, climate and biota. These point to the need for different land uses and land use regulations within an area and between areas. Vast areas of the Arctic Islands can be handled quite differently in exploration procedures than in the Low Arctic of northern Yukon and the Mackenzie Delta, yet small areas in the islands are comparable in terrain and biotic sensitivity to those of the Delta.

Data will be presented from some of the ecological research being conducted by government agencies, industry, and university groups to determine the environmental limits of Arctic exploration, oil and gas field development, and the impact of pipe-lines on arctic and subarctic ecosystems. Preliminary comparisons on seismic operations, use of summer and winter roads, revegetation trials and recovery of vegetation from spillage of crude oil or diesel fuel can now be made with landscape units of the Delta and, in some cases, between the Delta and the Arctic Islands. Data will also be presented on the Devon Island IBP High Arctic Ecosystem study, including information on how a natural ecosystem functions and some of the limits to its manipulation.

Bolstad, Roger (1971)
Catline rehabilitation and restoration. Proceedings - Fire in the Northern Environment - a symposium (ed. C.W. Slaughter, R.J. Barney & G.M. Hansen) U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station: 107-116.

Severe erosion has resulted in the past from bulldozer-constructed fire-lines in permafrost terrain. In an attempt to reduce erosion and gullying, several water-barring techniques and seeding treatments were tested on permafrost and nonpermafrost catlines. Standard water bars and berm dikes constructed at 30- to 50-yard intervals on sloping terrain were effective in reducing erosion. Vegetative check dams on permafrost soils were ineffective. Seed growth was more successful on permafrost than on nonpermafrost soils. Fertilized lines resulted in better seed success than unfertilized lines.

Brown, J., Rickard, W. & Vietor, D. (1969)
The effect of disturbance on permafrost terrain. U.S. Army, CRREL Special Report 138: 9 p.

CONCLUSIONS

The results of our 1969 summer observations reemphasize the importance of the surface layer in preserving permafrost terrain and provide data which demonstrate the magnitude of changes which occur in a single summer following natural or man-made changes. Essentially, any disturbance which eliminates or greatly reduces plant growth will result in an increased thaw. If the vegetative cover is physically damaged and mineral soil is exposed the increased thaw will be accompanied by erosion. A twofold increase in thaw after shearing the tundra vegetation was observed on carefully controlled experimental plots. The same increase was observed on mulched plots. Removal of vegetation by fire also results in an increased thaw. These increases are caused by the absorption of more energy into the soil through the darker surface cover. Establishment of new vegetative growth following damage will undoubtedly slow the rate of permafrost degradation and as shown by a recent Soviet report may result in the aggradation of permafrost. It is recommended that all vegetation or restoration studies of tundra measure thaw penetration under revegetated and controlled unvegetated sites to determine the magnitude of these differences.

Brown, R.J.E. (1966)
Influence of vegetation on permafrost. Research Paper No. 298, Division of Building Research, N.R.C., Ottawa, Reprinted from Proceedings: Permafrost International Conference, November, 1963, pp. 20-25.

The energy balance and thermal properties of permafrost are influenced by vegetation. Vegetation also influences climate, terrain and drainage and is useful as a permafrost indicator. Changes in vegetation cover influence depth of thaw, depth to permafrost, thermal regime of permafrost, temperature regime of the air above permafrost, and the extent and thickness of permafrost.

Burt, Glenn R. (1970)
Summer travel on the tundra with low ground pressure vehicles. University of Alaska, Institute of Arctic Environmental Engineering, Note 7004: 9 p.

Describes effects of Nodwell FN400 with "flat" tracks, 6-wheel and 4-wheel Rolligons and 4-wheel Carey. Effects of vehicle movements:

1. <u>Marks on the tundra</u>: Travel over thawed or frozen tundra can create visible marks. Some opinions claim any mark is detrimental and any operation leaving a mark should not be allowed;
2. <u>Erosion of the land</u>: In areas of relief or sloping topography extensive erosion can occur when destruction of the tundra mat concentrates water movement;
3. <u>Formation of lakes and ponds</u>: Where the terrain is relatively level, thaw of high water content permafrost following tundra destruction can create new ponds or lakes.

Code, J.A. (1973)
The stability of natural slopes in the Mackenzie Valley. Report of Activities, Part A April to October 1972., Canada, Geological Survey, Paper 73-1A; 224-225.

A study of the stability of banks of the Mackenzie River and its tributaries within the plains region was carried out between Fort Providence and Fort Good Hope. Slopes were mapped according to an engineering-geological classification which is intended to convey information, applicable to engineering purposes, which relates stability to the geology and the geometry of the slopes. Erosion of the river banks is accomplished by a range of types of mass movement and mass transport. The most significant mass movement, from an engineering standpoint, involves Quaternary and Cretaceous sediments. In order to indicate the importance of the scale of these failures they are initially classified either as relatively small active layer failures or as the larger, retrogressive types which characteristically involve the movement of much larger quantities of material. Although the latter type would present a more immediate threat to such nearby facilities as road, pipelines or structures their occurrence is somewhat predictable as they are associated with certain geological and topographic settings which can be avoided by construction activity.

Datskii, N.G. (1950)
Ground swelling under railway beds under permafrost conditions. Translated by E.A. Crolomshtok, the Stefansson Library, New York, 1950, for St. Paul District, Corp of Engineers, U.S. Army. 12p.

The papers describe observations on the life-cycles of swellings in permafrost disturbed by the construction of railway beds. The railway beds are classified as to position (e.g. in cuts, flat areas, or embankments) and swellings are explained on the basis of the hydrological conditions of each position.

De Leonardis, Salvatore (1971)
Effects of fire and fire control methods in interior Alaska. Proceedings - Fire in the Northern Environment - A symposium (ed: C.W. Slaughter, R.J. Barney & G.M. Hansen). U.S. Forest Service, Pacific Northwest Forest & Range Experiment Station: 101-105.

The taiga forest of interior Alaska lies within a broad zone of discontinuous permafrost. Although the gross effects of wildfire on vegetation and wildlife are fairly well known and understood, there is still a lack of knowledge on the effects of fire on interior soils and especially in permafrost soils. Serious erosion problems can occur in fine textured frozen soils with a high ice content. Fireline construction with tractors in silty permafrost soils can lead to gross gully erosion unless proper safeguards are undertaken. In some areas, catline construction has been estimated to have caused more erosion in the past than the actual effects of the fires.

Ferrians, O.J. Jr. (compiler) (1969)
Selected references on permafrost, and related engineering problems in Alaska. U.S. Geol. Survey, Mimeo. Rept. 21 p.

Some 250 unannotated citations.

Ferrians, O.J. Jr., Kachadoorian, R. and Greene, G.W. (1969)
Permafrost and related engineering problems in Alaska, U.S. Geol. Surv., Prof. Paper 678: 37 p.

ABSTRACT

Permafrost, or perennially frozen ground, is a widespread natural phenomenon. It underlies approximately 20 percent of the land area of the world. The permafrost region of Alaska, which includes 85 percent of the State, is characterized by a variety of permafrost-related geomorphic features including patterned ground, pingos, thaw lakes, beaded drainage, thaw or thermokarst pits, and muck deposits. Known permafrost thickness ranges from about 1,300 feet near Barrow in northern Alaska to less than a foot at the southern margin of the permafrost region. The distribution of permafrost is controlled by climatic, geologic, hydrologic, topographic, and botanic factors.

The extensive permafrost region of Alaska poses special engineering problems for the design, construction, and maintenance of all types of structures. Lack of knowledge about permafrost has resulted in tremendous maintenance costs and even in relocation or abandonment of highways, railroads, and other structures. Because of the unique geologic-environmental conditions that exist in permafrost areas, special engineering procedures should be used, not only to minimize disruption of the natural environment, but also to provide the most economical and sound methods for developing the natural resources of the permafrost region of Alaska.

CONCLUSIONS

Construction and maintenance of structures underlain by permafrost pose a wide range of problems. Engineers, designers, and construction and maintenance personnel are continuously plagued by severe frost heaving of structures, subsidence due to melting ground ice, soil creep or solifluction, landslides, and icings related to the presence of permafrost.

Some guidelines that can be followed to minimize the adverse effects of permafrost and frost action upon structures are summarized below.

1. Wherever possible, locate structures on coarse-grained materials. Avoid fine-grained, poorly drained, ice-rich sediments, since they are subject to much greater frost heaving and, if the permafrost is thawed, to greater differential settlement.

2. Insofar as possible, make any gravel pad - whether it be for a roadway, railroad grade, building site, airstrip, or drilling site - sufficiently thick to prevent permafrost from thawing.

3. Provide ample and proper drainage around any structure to prevent the thawing of permafrost and to minimize frost action and icings.

4. For heated buildings, whenever possible provide space for circulating air between the surface of the ground and the floor to minimize the transfer of heat into the ground.

5. Avoid the disruption or destruction of the vegetation overlying permafrost by using such techniques as end-dumping. Restrict tracked vehicles, trucks, and other heavy equipment to roads and do not permit them on the tundra

or vegetation where they will destroy its insulating quality and cause the permafrost to thaw.

6. Minimize frost heaving of supporting piles by providing the best possible drainage or by anchoring them securely in permafrost if feasible.

7. Avoid borrow pits upslope or downslope from structures. Thawing of the sites may cause drainage problems or damaging slumps and land slides.

8. Where parallel linear structures - such as pipelines, roads, or telephone lines - follow the contours of the slope, minimize disruption of the vegetation so that slumping along one structure will not damage the other.

9. Consider the following problems when pipelines are laid across creeks or rivers: a) If the pipeline crosses the creek or river underground, it may be damaged by the slumping of huge blocks of permafrost undercut at the banks, or it may be exposed by erosion and damaged by boulders, ice, or other debris during flood stage. b) Pipelines placed on the surface of a flood plain may be subject to inundation and possible damage by ice and floating debris.

10. Avoid construction in areas with natural icings whenever possible, or if such areas must be utilized, provide diversionary drainage.

The guidelines given above cannot be successfully applied without a thorough understanding of the thermal and mechanical problems unique to permafrost regions. Engineering procedures based on such an understanding should permit optimum utilization of the resources in the far north at a minimum overall cost and with a minimum disruption of the natural environment.

French, Hugh M. (1971)
Terrain disturbance associated with oil company activities in permafrost; Banks Island, N.W.T.; Winter 1970/71.MS. rept. to D.I.N.A., 13 p.

Study undertaken in July 1971. "This report is merely a descriptive preliminary account of selected observations ...."

Conclusions "It would appear that winter operation, undertaken when the soil is frozen, has had minimal terrain disturbance effects. In view of the harsh climatic environment at the time of operations, most reasonable attempts were made to prevent any terrain damage. That which has occurred is, in general, slight and in all cases extremely localized. It would appear that terrain completely free of vegetation is the most suitable for surface vehicles in winter since it provides a firmer, smoother surface than vegetated areas, when both are frozen. This is in contrast to summer conditions when it is generally advisable to traverse the vegetated areas in regions of marginal transportation. However, it is clear that no oil company activities ought to be sanctioned when the ground is unfrozen (i.e. during the summer months). During winter months, if oil company exploration activities are allowed, due consideration must be taken of topographic conditions, surficial materials, vegetation cover, soil micro-relief, and permafrost conditions. The Rolligon equipment appears to have worked well and should continue to be used as an alternative to metal tracks".

French, H.M. (1973)
Geomorphological processes and terrain sensitivity, Banks Island, District of Franklin. Report of Activities, Part A, April to October 1972. Canada, Geological Survey, Paper 73-1A: 220-223.

b) Terrain sensivitity and thermokarst studies

Several acres of disturbed terrain adjacent to the Sachs Harbour airstrip are being observed. A thin veneer of glacial sands and gravels, which overlie silts and sands, was stripped and removed during the construction of the airstrip in 1962. Thermokarst subsidence has occurred subsequently on both sides of the airstrip. The thermokarst terrain is characterized by irregular hummocky topography, standing water and pools, and a number of small, interconnected linear depressions. The hummocks are commonly 10 to 15 feet in diameter and give a relative relief of between 3 to 5 feet to the terrain. Air photographs reveal the depressions to follow broad patterns similar to the ice-wedge polygons of adjacent undisturbed areas.

Detailed levelling of selected areas of thermokarst has been undertaken with a view to ascertain the rate of change of thermokarst topography. Thermocouples have been installed to investigate the thermal regimes of disturbed and undisturbed terrain.

Gol'dtman, V.G. (1964)
The aims of permafrost studies in the northeast of the USSR. Problems of the North No. 7: 49-56.

Considers pre-construction thawing of permafrost at construction sites, and prevention of fall freeze back by insulation (mulch) or sprinkling, to lower costs of operations involving movement of earth material (excavation to dumping).

Grave, N.A. and Nekrasov, I.A. (1962)
Some observations on thermokarst in the vicinity of the settlement of Anadyr. Problems of the North No. 4: 165-172.

Thermokarst is currently developing only in places where the surface of the tundra has been severely damaged, usually because of human activity. Traffic near the Anadyr Cryological Research Station between 1945 and 1950 led to complete destruction of vegetation over a wide area. Subsequent thermokarst produced a series of lakes, and gullies as much as 3 m deep following ice wedges. The average depth of thaw has increased by 11 cm (by 1963), and there has been a general subsidence of the ground surface.

Haley, J.F. (1955)
Thawing beneath buildings constructed on permafrost near Fairbanks, Alaska. Miscellaneous Paper 12, Arctic Construction and Frost Effects Laboratory, New England Division, Corps of Engineers, U.S. Army, Boston, 8 p.

The rates of thawing of permafrost and subsidence of buildings at different conditions as described in this paper.

Harwood, T.A. and Yong, R.N. (1972)
Northland vehicle considerations. Proceedings, Canadian Northern Pipeline Research Conference, 2-4 February, 1972. (ed: R.F. Legget and I.C. MacFarlane). Canada, NRC/ACGR, Tech. Memo. 104: 129-143.

ABSTRACT

Basic fundamentals of wheel or track vehicle interaction research are outlined briefly together with the research carried out in this field in Canada. A review of experience with surface vehicles tested recently in Canada shows that optimum design conditions have yet to be met, and future developments for a Northland vehicle must meet a multiple set of criteria. The recent Quadripartite table exercise for design of an optimum vehicle to be used over representative Northern terrain is cited as an example.

It is observed that to meet zero environmental disturbance conditions, requirements can be specified which would fulfill mission and other conditions. Degradation in aggressive performance of a tracked vehicle can be programmed and designed for, which will cause little or no damage to the surface vegetation in open tundra or in permafrost areas.

R.K. Haugen and J. Brown (1971)
Natural and man-induced disturbances of permafrost terrane in Environmental geomorphology (ed.: D.R. Coates): 139-149, 7 figs., 7 refs. (Binghamton, N.Y.: State Univ. of New York, Publications in Geomorphology).

ABSTRACT

The extreme sensitivity of permafrost terrane to disturbance is particularly evident in the ice-rich permafrost regions of Alaska. Problems arise because of the fragile equilibrium between the surface cover and the underlying wet soils and permafrost. Both natural and man-made disturbances affect this balance. The susceptibility of permafrost terrane to degradation is primarily related to the insulation qualities of the surface layer, and the ice content of the frozen soil beneath it. In the north where the surface organic layer is the thinnest and the ice content of the soil is highest, sensivitity to disturbance is the greatest. In the southern permafrost zones, the organic mat is thicker, underground ice is discontinuous and often without surface expression, so the likelihood of degradation effects is more difficult to predict. Examples of long and short-term effects are cited. These include study plots where ground temperatures under various surface treatments have been measured over a period of years, as well as the present condition of disturbances which occurred many years ago. Finally, some engineering practices which permit human activity with minimum permafrost degradation are summarized, with the observation that man can live in harmony with permafrost terrane if appropriate knowledge and respect for the existing environmental equilibrium is applied.

Heginbottom, J.A. (1971)
Some effects of a forest fire on the permafrost active layer at Inuvik N.W.T. Proceedings of a Seminar on the Permafrost Active Layer, 4 and 5 May, 1971 (ed. by R.J.E. Brown), Canada, NRC/ACGR Tech. Memo. No. 103: 31-36.

The direct effects of forest fire on the permafrost active layer are relatively minor. Over the first few years the active layer becomes thicker, there is a slight decline in the ground surface elevation and the hummocky microrelief becomes less pronounced. More serious are the effects of bulldozing of fire guards, where the vegetation-peat insulating mat is completely removed. The active layer thickens more and quicker, with a marked decline in surface elevation.

Several minor active layer earth flows occurred in the burned area, mainly on south facing slopes. Such flows are common in, but not unique to, fire areas. The connection between fire and slope failure is not established.

Heginbottom, J.A. and Kurfurst, P.J. (1973)
Terrain sensitivity and mapping, Mackenzie Valley Transportation Corridor. Report of Activities, Part A, April to October 1972; Canada, Geological Survey, Paper 73-1A: 226-229.

Materials of each surficial geological map-unit have a different character and variable ground ice content. Peat is generally of low strength, highly compressible with moderate to high ground ice content; it is commonly unfrozen (fen) to depths of more than 6 feet. Clay, which is commonly mixed with silt and overlain by sand with a discontinuous organic cover, is generally highly plastic, with moderate to high ground ice content in the form of a reticulated network of segregated ice. Silty to clayey till, underlain by bedrock, has moderate ground ice content with segregated ice occurring as thin seams and thicker lenses. Ground ice content in sand and gravel is generally low or not present in the coarser deposits and low to moderate in finer sediments. Little ground ice is found in bedrock except in shale where a network of small ice-filled fractures was encountered at depths of from 100 feet to 150 feet.

Excessive compaction and/or removal of the vegetation cover by natural or other processes can lead to terrain subsidence, severe gullying, and ground ice and thermokarst slumping. Ice-rich clays and silty clays on hillsides and sloping banks are most prone to disturbance which can result in superficial mudflows and large flow slides.

Eight abandoned oil well sites were visited and at each one the aftermath of drilling and associated activities, which included airstrips, seismic trails, access roads, campsites, and staging areas were examined. The oldest site visited was abandoned in 1960, the most recent one in January 1971.

The disturbance immediately surrounding the well-heads and slush-pits is quite apparent. At most sites gravel and/or wood chips had been spread to minimize thermal disturbance. Wood chips can be quite effective for this purpose, for at Attoe Lake I-06 well-site, on 20 June 1972, the ground was thawed for only 10 cm below a 25-cm thick layer of wood chips, compared with 60 cm under burned ground and 42 cm under unburned ground well away from any disturbance. In general, the depth of thaw was greatest near the well-head, and decreased to the edge of the clearing. The depth of thaw was normally about 50 per cent greater in the well-head area compared with undisturbed terrain.

The three airstrips examined had suffered little disturbance other than removal of tree vegetation. The site requirements of a temporary airstrip - smooth, level ground - mean that they are often sited on terraces of granular, i.e., non-frost susceptible material or on broad organic deposits. Neither are prone to severe deterioration following the initial clearing.

Seismic trails were examined in about 15 locations on slopes of various angles and geological materials. The amount of disturbance appears to be due primarily to differences in original mode or construction of the trails - in cases where the humus and vegetation mat was removed, thawing and thermokarst have occurred. In other cases, only the removal of the trees indicates that any activity has taken place. Similar conclusions may be drawn from the access trails which were examined in nine locations.

Hemstock, R.A. (1953)
Permafrost at Norman Wells, N.W.T. Imperial Oil Limited, Calgary, 100 p.

This is a summary of information available on the Norman Wells area prior to 1950. It includes a description of the immediate effects of construction of buildings, roads, airfields, and communication lines on permafrost.

Hodgson, D.A. (1973)
Terrain performance, central Ellesmere Island District of Franklin. Report of Activities, Part A, April to October 1972. Canada, Geological Survey, Paper 73-1A: 185.

The effects of construction and vehicle operation on a variety of terrain types were observed concurrently with a reconnaissance of surficial materials and landforms (Project 720081). There are two principal areas of activity on the western Fosheim Peninsula.

1. Eureka weather station and airstrip, where poorly lithified, weathered shale (Deer Bay Formation) and marine silts and clays have been disturbed to varying degrees over the past 25 years.

2. The recent extensive oil and gas exploration which includes ground seismic surveys, use of bladed roads and airstrips, and intensive movement around drill sites.

Churning of the surface by vehicles only occurs during the early summer thaw, and the low precipitation and limited run-off retard expansion of disturbed areas by natural processes. However, roads and airstrips are visually prominent and induce vegetation changes so that it is unlikely that they will merge with the surrounding landscape.

Hogan, A.W. (1970)
Snowmelt delay by oversnow vehicles
Water Resources Research 8 (1): 174-175.
"Oversnow vehicles compact the snowpack several inches as a result of their passage; drifting snow tends to refill these tracks to ambient level. This repeated travel and drifting result in storage of much greater water content in the snowmobile trails than in the adjacent undisturbed snowpack .... and (a) time delay of snowmelt in an area travelled by oversnow vehicles."

"... travel by oversnow vehicles appears to have, in years of heavy snowfall, two beneficial effects: (1) increased infiltration where the water content has been increased in disturbed snow, and (2) delay of snowmelt on erosion-prone logging roads until after maximum runoff has occurred."

Hok, Jerome K. (1969)
A reconnaissance of tractor trails and related phenomena on the north slope of Alaska. U.S. Dept. of Interior, Bureau of Land Management: 66 p.

Study undertaken in summer of 1969.
Goals of project:
"1. To obtain broad preliminary observations of tundra vegetation recovery upon tracked vehicle trails of known history

2. The compilation of a bibliography on studies of this subject
3. The development of working hypotheses about the effects of vehicles on tundra vegetation, and the formulation of a research program to intensively study specific aspects of the problem."

Results - see summary in Roberts-Pichette (1972, p. 113-115).

Hume, J.D., Schalk, M., and Hume, P.W. (1972)
Short term climate changes and coastal erosion, Barrow, Alaska. Arctic, 25 (4): 272-278.

Effects of Construction

Borrowing of beach sediment at Barrow for construction purposes has been going on since at least 1945. During the summers of 1961 and 1962, measurements showed how the removal in 1961 of about 30,000 cu. m. of beach sediment resulted in an average retreat of the shoreline in the borrow area of 3.1 m. (Hume and Schalk 1964). The beach from which the sediment was removed lay chiefly between Browerville and Camp. Some borrow came from the Camp section itself. During the late 1960s, construction of a new airport, large enough for jet aircraft, involved the removal of most of the coarse sediment from the beach southwest of Barrow village for about 4 km. Retreat of the shoreline and bluffs occurred as a result of this borrowing (Fig. 3).

Isaacs, R.M. (1973)
Engineering geology, Mackenzie Valley Transportation Corridor. Report of Activities, Part A, April to October 1972. Canada, Geological Survey, Paper 73-1A: 230-231.

Very limited drilling of the Canol Road, at about 6½ miles along the road from the Mackenzie River, indicated that permafrost immediately beneath the road may have disappeared entirely or has degraded to a great depth. This seems substantiated by recent shallow seismic work by J.A. Hunter (Project 680037) and, as it may be very significant in the design of roads and pipelines in the north, it should be investigated during the next field season.

Ivanovskii, A.I. (1964)
Transformation of nature and ways of developing agriculture in the far north. Problems of the North No. 7: 1-19.

Describes various methods for "thermal improvement" of soil, i.e.: planned degradation of permafrost, namely:

- holding back snow in fall plus snow removal in spring
- development of protective strips of bush and forest
- steaming of fields
- electrical heating of fields
- harrowing of fields
- sowing of winter crops
- mulching in fall
- ridging and rowing of crops
- artificial irrigation

J.R. (Ramsay, James?) (1969)
Wonderland revisited. Sierra Club Bull. 54 (10): 10-13.

Discusses the possible impacts of development of Alaskan oil deposits on the environment. Includes excellent photographs of terrain damage due to road construction.

Kallio, A. and Reiger, S. (1969)
Recession of permafrost in a cultivated soil of interior Alaska. Soil Science Society of America, Proceedings 33 (3): 430-432.

Describes the effects of clearing, cultivating and seeding of test plots on soil temperatures within & just below the active layer. Under perennial grass and under potatoes the active layer thickens in three years from about 1 m to about 5 m.

Kerfoot, D.E. (1972)
Topographic aspects of artificial disturbances to the tundra in the Mackenzie Delta area, N.W.T.
Mackenzie Delta Monograph. (ed. D.E. Kerfoot), St. Catharines, Ont.: Brock University for 22nd International Geographical Congress: 157-174.

CONCLUSIONS

Four basic relief components may contribute to the topographic aspects of disturbances produced by the cross-tundra movement of vehicles. These components are related to: (1) the physical removal of material from the tundra surface, (2) a redistribution of this material on or adjacent to the route, (3) thermokarst subsidence, and (4) thermal or mechanical erosion by running water. The first two components are directly associated with the immediate passage of the vehicles and their magnitude can be controlled by the adoption of suitable operational methods in the exploration programme. The other two components are related to a subsequent accentuation of the topographic aspects following the initial disturbance to the tundra surface. Field studies demonstrate that thermokarst subsidence is the most important process involved in this accentuation, and that erosion by water moving along the subsided areas is seldom of more than minor significance.

Klyukin, N.K. (1964)
Questions related to ameliorating the climate by influencing the snow cover. Problems of the North No. 7: 67-90.

Emphasises removal of the snow so that fields can be worked earlier, and melting of snow for improved water supply and planned degradation of permafrost.

Kovsak, V.K. (1964)
Means of cross-country land transport in the far north. Problems of the North No. 5: 110-113.

A good summary of the state-of-the-art, the vehicles then available (Russian, Canadian and American) and of future requirements.

Kriuchkov, V.V. (1968)
Necessity of soil conservation in the Far North, Priroda No. 12: 72-74. Trans. from Russian by E.R. Hope. Canada, Defence Research Board, Defence Scientific Information Service, T523R: 5p.

Suggests that fires, far from ameliorating soil conditions in permafrost areas, actually lead to a rise in the permafrost table and a shallower, colder active layer which inhibits regrowth of trees.

Lachenbruch, A.H. (1957)
Three-dimensional heat conduction in permafrost beneath heated buildings. Geological Survey Bulletin 1052-B, U.S. Geol. Survey, Washington, pp. 51-69.

A theoretical treatment of heat flow from man-made structures in permafrost areas is given. Heated buildings are referred to in this report, but stripping of vegetation or road construction are suggested to warrant similar treatment.

Lachenbruch, A.H. (1970)
Some estimates of the thermal effects of a heated pipeline on permafrost. Geological Survey Circular 632, U.S. Geol. Survey, Washington, 23 p.

Basic principles of heat conduction are applied to simplified permafrost models to suggest effects of heated pipelines, conditions controlling them, and the ranges of physical properties within which these effects may cause problems. The extent of thawing, with time, is given. Changes in the subsurface materials and the terrain as a result of thawing are suggested.

Legget, R.F. (1959)
Geology and transportation routes. Technical Paper No. 64, D.B.R., N.R.C., Ottawa, 6 p., Reprinted from Roads and Engineering Construction, Vol. 97, No. 2.

Disturbance of permafrost affects thermal regime and ground-water in permafrost areas for a period of several years. Construction of roads may initiate landslides or rock falls in permafrost areas.

Lewellen, Robert I. (1970)
Permafrost erosion along the Beaufort Sea Coast. (Denver, Colorado): University of Denver, Dept. of Geography & Geology: 25 p.

The purpose of this report is to illustrate and focus attention on the permafrost erosion along the Beaufort Sea coast of Northern Alaska. The thermal erosion of permafrost along the coast results in shore line recessions as great as ten meters (33 feet) per year. The recession is caused by wave action and air temperatures thawing the frozen sediments. The two areas which are discussed in detail are Elson Lagoon and Flaxman Island. Elson Lagoon is located south of Point Barrow, Alaska. Flaxman Island is adjacent to the Prudhoe Bay oil development activity. The receding shore lines must be considered before a logical definition of this region is possible.

Lewellen, Robert and Brown, Jerry (1969)
Man induced erosion of permafrost.
20th Alaska Science Conference, College, Alaska, 24-27 August, 1969.

The activity of man in the Barrow, Alaska vicinity has inadvertently accelerated the erosion of permafrost. Footprint Creek is rapidly entrenching as a result of draining three large lakes. The drainage of two lakes increased the drainage area four-fold. The draining of the third lake established a new erosional base level for the creek. Sequential aerial photography taken from 1945 through 1968 has been utilized to reconstruct the geomorphic processes. Ground measurements and observations were made. The record precipitation, in 1963, resulted in a knickpoint retreat of twenty-eight meters due to the thermal erosion of high-ice content, fine-grained sediments. A snow road, constructed in the winter of 1963 and 1964, was effective in temporarily damming the runoff waters. These waters caused extensive thermal erosion. During the summer of 1964, water-hauling vehicles destroyed the tundra adjacent to the lower Footprint Creek channel. Gullies are developing along the vehicle tracks.

Lewin, J.D. (1948)
Dams in permafrost. Public Works, May, 1948

An account of the effects of water storage reservoirs and earth fill on permafrost is presented. Calculations of heat required to thaw permafrost at arbitrary temperatures and ice contents and the depths of water at arbitrary temperatures required to provide the required quantity of heat are given. On the basis of these calculations, the author suggests that the permafrost will be thawed to a depth of one-quarter of the depth of the water in the reservoir.

Lloyd, Trevor (1944)
Oil in the Mackenzie Valley. Geographical Review 34 (2): 275-307.

p. 299: Canol contractors early discovered one way in which the climate would make operations difficult. In August, 1942, an attempt was made to construct a base camp on the west bank of the Mackenzie near Ogilvie's Island, 17 miles downstream from Norman Wells, where the pipe line was to have crossed. Bulldozers quickly removed the light brush and moss that covered a low terrace. The frozen gravel and clay thawed when exposed to the warm air,[37] and soon innumerable small streams were running across the foreshore. The more the bulldozers were used in an attempt to clean up the site, the muddier it became. Finally, at the end of the month, as the close of the navigation season approached, the site was abandoned to the elements, and a new one was selected on the same side of the river but within 3 miles of Norman Wells. Here the winter camp was laid out that developed into Camp Canol, the permanent eastern base of operations. It is, of course, very muddy in summer.

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37 Drilling at Norman Wells shows that the lower limit of permanently frozen ground is about 90 feet below the surface. Ice was found within 15 inches of the surface in mid-August, but cleared land thaws to more than 4 feet.

Lotspeich, F.B., & Mueller, E.W. (1971)
Effects of fire in the taiga on the environment. Proceedings - Fire in the Northern Environment - A Symposium (eds: C.W. Slaughter, R.J. Barney & G.M. Hansen). U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station: 45-50.

"Findings from a study of fire effects on the aquatic environment lead to the conclusion that the fire had fewer deleterious effects than did activities from fighting the fire - improper siting of "cat" lines as an example".

"If burning is not severe enough to destroy the usual deep moss cover of most of the taiga, erosion does not present a problem. Permafrost may melt to greater depths for a few years after a fire, but this seldom introduces a problem of erosion unless the overlying vegetation mat is removed, either by severe burning or heavy equipment."

Lotspeich, F.B., Mueller, E.W. & Frey, P.J. (1970)
Effects of large scale forest fires on water quality in interior Alaska. U.S. Federal Water Pollution Central Administration; Alaska Water Laboratory: 115 p.

"In general, burning was not severe enough to destroy the entire organic layer.

The depth of thawing was not affected by the fire.

The only evidence of increased erosion was in the fire trails.

Fire control methods may cause more serious, long-lasting damage to the aquatic ecosystem within the burned area than the fire itself. In developing a fire control plan, sufficient forethought should be given to the possible consequences of control measures to prevent extensive damage to the taiga ecosystem."

Mackay, J.R. (1970)
Disturbances to the tundra and forest tundra environment of the western Arctic. Canadian Geotechnical Journal 7 (4): 420-432.

The more important physical disturbances to the tundra environment are discussed with examples. Thermokarst subsidence, not thermal erosion, is shown to be the dominant result of man-induced disturbances, such as those caused by the bulldozing of seismic lines and fire-breaks. It is shown that a clear distinction between thermokarst subsidence and thermal erosion is necessary, if the causes of the disturbances are to be prevented and minimized, or the results treated. The typical surface disturbance to the tundra results in a deepening of the active layer. Therefore, foreknowledge of the effect of a disturbance on deepening the active layer, together with information on the ice content of the permafrost affected, makes it possible to predict the amount of thermokarst subsidence likely to take place. Three practical examples of three types of ground disturbance are given: a fire near Inuvik, N.W.T.; a patch of vegetation trampled and killed by a dog at Garry Island, N.W.T.; and seepage down a walking trail in an ice-wedge area at Garry Island, N.W.T. The effects of the disturbances are illustrated and discussed.

Mackay, J.R. (1971)
Ground ice in the active layer and the top portion of the permafrost. Proceedings of a seminar on the permafrost active layer, 4 and 5 May 1971 (ed.: R.J.E. Brown). Canada NRC/ACGR Tech. Memo 103: 26-30.

Conclusions

"1. The top several feet of the permafrost tends to be an ice rich zone which is easily affected by a surface disturbance. In sands, the amount of excess ice is usually negligible. In fine-grained and organic soils, it may be in the hundreds of per cent. The high ice content generally results from a combination of an upward aggradation of the permafrost as a result of a climatic change; burial as a result of soil creep; and growth of ice in horizontal cracks open to the surface.
2. Other things being equal, upper slopes and summit positions have less ice at the top of the permafrost than lower slopes and flats.
3. Downslope soil movement on hill slopes may obliterate all surface indications of large ice wedges beneath.
4. Fine-textured soils which either overlie coarse-grained soils, or are interstratified with them, have provided ideal conditions for the growth of massive icy bodies where the permafrost aggraded in a closed system.
5. A knowledge of the past geologic and thermal history of a region is, in most areas, indispensable for an understanding and prediction of the present distribution of underground ice."

Mackay, J.R. (1972)
The world of underground ice. Annals of the Association of American Geographers 62 (1): 1-22.

ABSTRACT

Underground ice is restricted to permafrost areas where its distribution is sporadic and often unpredictable. A knowledge of the distribution and abundance of underground ice is essential to northern development, because a variety of man induced disturbances can cause underground ice to thaw, often with serious consequences. The criteria for a classification of the principal types of underground ice are the source of the water prior to freezing and the processes which transfer water to the freezing plane. The origin of massive icy bodies in the Western Arctic of North America is explained by a water expulsion theory. The excess water now found in the icy bodies is attributed to water expelled from coarse textured sediments by the downward growth of permafrost. The suggested mechanism is illustrated by three pingos which have grown since 1950. The role of glaciation in the formation of relic offshore permafrost in relatively shallow Arctic coastal areas is examined. The evidence suggests that offshore permafrost is present in some shallower portions of the Beaufort Sea from northeastern Alaska eastwards to the high Arctic islands of Canada. If offshore permafrost with underground ice is present, then thermal disturbance problems must be taken into consideration in future offshore exploration.

Mackay, J.R. (1972)
Permafrost and ground ice. Proceedings, Canadian Northern Pipeline Research Conference, 2-4 February, 1972 (ed.: R.F. Legget and I.C. MacFarlane). Canada, NRC/ACGR Tech. Memo. 104: 235-248.

ABSTRACT
The permafrost terrain of northwest Canada has a great variability in its ground ice content. Extensive areas are largely ice free, and construction there can probably be handled by conventional means. Other areas contain abundant ground ice, of several types, down to the depth which is subject to thermal disturbances induced by construction or hot buried pipelines. Therefore, the distinctive permafrost problems are those involving high ice content ground, such as its distribution, both vertically and horizontally, and its engineering properties, when frozen and thawed.
All ground ice formed either during the growth of permafrost or subsequently thereafter. An attempt is made to discuss, in broad terms, some aspects relating to the growth of permafrost and the origin of ground ice in the Yukon Coastal Plain, Mackenzie Delta area, and Lower Mackenzie Valley. It is suggested that research into the origin of ground ice could contribute towards a more economical mapping program, a fuller understanding of the properties of frozen ground and a better prediction of thermal disturbances.

Mozeson, D.L. (1961)
Conservation in the north. Problems of the North No. 2: 235-238.

Describes accelerated run-off and erosion, plus degree thawing and drying of ground resulting from many years of over exploitation of timber reserves at certain sites in East Siberia. Similar effects are also found to follow forest fires. Describes management procedures under discussion to rectify the situation.

Pegau, Robert E. (1970)
Effect of reindeer trampling and grazing on lichens. Journal of Range Management 23 (2): 95-97.

In July 1966, some 1,000 reindeer, running to avoid insects, milled about in a tight circle, 75 to 100 ft. in diameter, on top of a low pingo mound near Nome, Alaska. The mound was covered with typical dry tundra; the animals milled around for about 12 minutes and then moved away. During the milling, the vegetation was thoroughly trampled and all that remained were broken fragments and shredded moss. The insulating effect of the vegetation was destroyed and within two days meltwater from the thawing subsoil seeped up through the moss and completely inundated the area. In 1967 the area remained flooded throughout the summer, in 1968 it was flooded until mid-June. By September 1968 the only vegetation to show any recovery was some sedges and mosses sprouting from buried rhizome fragments.

Péwé, T.L. (1954)
Effect of permafrost on cultivated fields, Fairbanks area, Alaska. U.S. Geological Survey, Bulletin 989-F: 315-351.

ABSTRACT

Permafrost affects agricultural development in many parts of Alaska. Its destructive effects on cultivated fields result chiefly from the thawing of large masses of clear ice in the frozen ground. If care is not exercised in selecting areas to be cleared for cultivation, thawing of permafrost may necessitate abandonment of fields or their reduction to pasture. The effects of permafrost on farming are well illustrated in the Fairbanks area, which lies in the Tanana Valley, the most extensive potential agricultural area in Alaska. Permafrost may be encountered nearly everywhere in the Fairbanks area except beneath hilltops and moderate to steep south-facing slopes. Sediments of the Tanana and Chena River flood plains (50 percent of the area) are perennially frozen to a depth of at least 265 feet, but not everywhere is permafrost encountered in a single layer. Permafrost on the flood plain affects soil drainage and temperature during the first few years after the clearing of the land, but this effect disappears after the permafrost table has been lowered. Because ground-ice masses are lacking, no undesirable mounds or pits are formed by thawing of frozen ground.

Alluvial fans, colluvial slopes, and lowlands, all consisting of silt, extend from the hills to the flood plain and are underlain by continuous permafrost, as much as 175 feet thick near the flood plain, but which thins toward the hills, pinching out at the base of steep south-facing slopes. Permafrost in the fans, slopes and lowland is characterized by masses of clear ice as much as 50 feet in the largest dimension. Removal of vegetation cover causes thawing of this ice. The thawing of the ice masses creates thermokarst topography - an uneven topography characterized by mounds, sags, sinkholes, tunnels, caverns, and short ravines.

Thermokarst mounds are polygonal or circular hummocks 10 to 50 feet in diameter and 1 to 8 feet in height, separated by trenches 1 to 5 feet wide. The trenches are formed by the melting of a polygonal network of ground-ice masses and subsequent subsidence of the ground leaving mounds in the intervening areas. Mounds generally begin to form in a cultivated field within 2 or 3 years after clearing.

Thermokarst pits are steep-walled pits, 5 to 20 feet deep and 3 to 20 feet across initiated by the melting of ground ice. Twenty-four thermokarst pits were found in cultivated fields of the Fairbanks area.

Alluvial fans, colluvial slopes and a small silt lowland comprise 27 percent of the Fairbanks area. Thermokarst mounds and pits are likely to form in cultivated fields on these slopes and lowland: these features may necessitate the abandonment of the field or reduction to pasture. In 1948, 32 of the 37 fields on the slopes and the lowland showed evidence of thermokarst action. Six of the 27 fields cleared before 1945 had been abandoned for more than 20 years, and in five others cultivation was attempted only on a part of the original cleared land. Mounds and pits had already begun to form in half of the 10 fields cleared between 1945 and 1948.

The northern part of the Fairbanks area (23 percent) consists of rounded, even-crested loess-covered hills 1,250 to 1,800 feet above sea level. Cultivated fields on the sout acing gentle slopes of the hills do not have mounds or pits because permafrost is absent.

The investment of labor and capital required for clearing land in Alaska makes careful selection of ground imperative. Where mounds develop, fields can be reclaimed by grading and a field can continue to be used if the mounds are repeatedly levelled as they reform. New pits can be filled as they appear. However, it is a costly fight and much time, money, and soil are wasted in such a perennial struggle. In permafrost areas land should be surveyed for its permafrost characteristics before development.

Rampton, V.N. and Mackay, J.R. (1971)
Massive ice and icy sediments throughout the Tuktoyaktuk Peninsula, Richards Island, and nearby areas, District of Mackenzie, Canada, Geological Survey, Paper 71-21: 16 p.

ABSTRACT

Massive bodies of subsurface ice and icy sediments are relatively abundant throughout the Tuktoyaktuk Peninsula, Richards Island, and nearby areas. A statistical study, based upon shot hole records, shows that massive ice is most common at a depth of about 40 feet. Icy sediments, where present, occur with relatively constant frequency to a depth of at least 140 feet. At Tuktoyaktuk, examples of massive ice and icy sediments are readily accessible for examination in man-made excavations and coastal exposures.

Rickard, Warren (1972)
Preliminary ecological evaluation of the effects of air cushion vehicle tests on the arctic tundra of northern Alaska. U.S. Army, CRREL, Special Report 182: 26 p.

Of prime concern in the Arctic is the need for a nondestructive and efficient means of transportation over both frozen and unfrozen arctic terrain. As part of the effort to develop such a means, the Advanced Research Projects Agency established a program to determine the potential for using an air cushion vehicle (ACV). Studies on the effects of ACV tests were conducted in two areas at Barrow, Alaska. One area was drained lake bottom with a fairly homogeneous vegetation cover and soil type. The second area, much drier than the first, consisted of low-centered polygons composed of a set tundra soil and a varying vegetation complex. The initial effects of the ACV tests in both areas were quite similar. The amount of litter decreased from 40-44% to 0-2% as the number of vehicle passes increased. The amount of standing dead vegetation decreased much less. Quantities of living vegetation remained fairly constant regardless of the number of vehicle passes, with clumps of mosses being torn loose in the low-centered polygon areas. The albedo also changed; this may become important over a long period with respect to the amount of solar radiation absorbed by the lighter and darker terrain surface.

Roberts-Pichette, P. (1972)
Annotated bibliography of permafrost-vegetation-wildlife-landform relationships. Canada, Forest Management Research Inst., Information Report FMR,-X-43, 350 p.

"This bibliography contains almost 500 titles chiefly from post 1945 North American, European and USSR literature on the arctic and subarctic regions of the world. Although concerned primarily with land sensitivity in the north, titles of taxonomic, ecological, geological, geographical, meteorological and permafrost studies and reviews have been included. Quotations have been selected to give special emphasis to the ecological problems resulting from man's increased activities in the North and also to the accumulating of information on how to repair, reduce or circumvent environmental damage."

Skrobov, V.D. and Shirokovskaya, E.A. (1968)
The role of the arctic fox in improving the vegetation cover of the tundra. Problems of the North No. 11: 123-128.

Refers to one specific den near the Yuribei River in the Yamal. The den occupied an area of 120 m^2 and had 15 exits; it had been developed over several decades. 60% of plant species abundantly distributed over the den area (mainly grasses) were absent from the terrain around, and less than one third of the species of the surrounding terrain <u>also</u> occurred on the den area. Absences included almost all lichens, cottongrass, sphagna, cloudberry, cassandra, etc. The vegetation of the den area was quite luxuriant. Active fox dens are marked by yellow patches of excavated sand. The permafrost surface was at 180 cm, twice the depth outside the den area.

Slaughter, Charles W. (1971)
Fire and resources in the subarctic-panel discussion. Proceedings - Fire in the Northern Environment - A Symposium (ed.: C.W. Slaughter, R.J. Barney & G.M. Hansen), U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station: 249

"... the entire questions of fire history and the role of fire in subarctic ecosystems remain open for exploration .... Does fire over permafrost terrain result in melting of the frozen ground from increased exposure to sunlight and increased radiation absorption by blackened surfaces, or might a shallower "active layer" (depth to permafrost) result, as suggested in a recent Russian paper?"

Slaughter, C.W., Barney, R.J., & Hansen, G.M. (eds.) (1971)
Fire in the Northern Environment - A Symposium; U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station: 275 p.

Proceedings of a symposium held at the University of Alaska, College, Alaska, April 13-14, 1971. Comprises 22 papers, panel discussion and summary. Pertinent papers are abstracted separately.

Solovev, P.A. (1971)
Zonality of the strength of the seasonally thawing layer and its mapping in western and southern Yakutia. U.S.A./CRREL, TL-233: 8 p.

Presents a map of western and southern Yakutia (essentially the Lena River watershed) showing the general depth of penetration of the annual surface thaw wave in zones, separated by crude isolines. The depths are given in terms of a disturbed site immediately before or just after the construction phase. Values are given for depth of thaw for a sandy soil and for a clayey soil.

Spiridonov, V.V. (1972)
Research in the field of transmission pipeline construction in northern regions. Proceedings, Canadian Northern Pipeline Research Conference, 2-4 February, 1972. (ed.: R.F. Legget & I.C. MacFarlane), Canada, NRC/ACGR Tech. Memo 104: 277-282.

p. 279: 1. Study of the pipeline interaction with environment. This consists of two mutually related problems. The climatic and ground-freezing conditions in the areas of production and pipeline routes and the prediction of ground-freezing condition changes as a result of the construction and operation of pipelines and above-ground structures.

To study climatic peculiarities of the regions we use, first of all, the data from the hydro-meteorological service of the USSR and from special scientific-research stations. More large scale data can be obtained from specially organized observation points and permafrost offices (stations), which have been functioning at every project located in permafrost regions. An extensive mapping and air photo survey is being conducted for the selection of sites for above-ground facilities and routes for pipelines. The survey data allow us to evaluate with sufficient accuracy the ground-freezing and hydrogeological conditions at the sites and along the right-of-way of the pipelines. The amount of the surveying for northern pipelines is considerably greater than that in the central part of the country and depends on the pipeline diameter, method of construction to be used and site or route complexity. The right-of-way for northern pipelines is significantly wider than in conventional conditions, both on the stage of working on project specifications and in preparing working drawings. The great length of the pipeline routes requires large amounts of surveying in the field which can be carried out by qualified specialists. Though we use mechanized and physical methods of permafrost research, taking into consideration the seasonal character of certain types of survey, still this work is very time consuming. Therefore, we conduct this work at the stage of the project specifications development for the proposed sites and pipeline routes. On the basis of these investigations we classify locations of specific character; this allows us to select optimal pipeline routes taking into account ground-freezing conditions and using electronic computers. The correct selection of the route for a northern pipeline is practically impossible without a comprehensive study; and the losses due to mistakes incurred by the absence of needed information would be considerably higher than the cost of research.

Taber, Stephen (1943)
Some problems of road construction and maintenance in Alaska. Public Roads, Vol. 23, No. 9, pp. 247-251.

Observations of frost-heaving, downslope creep, mud-flows, slumps, sinking, and icings caused by the construction of roads in permafrost areas are described.

Tolstov, A.N. (1962)
The region of intensive erosion and thermokarst. Problems of the North No. 4: 157-163.

Comments, with regard to the initiation of thermokarst: "In this connection human activities that disturb the vegetation cover (paths, tractor trails, etc.) are also of a certain importance in the north."

Tsytovich, N.A. (1950)
An investigation of elastic and plastic deformation of frozen ground. Translated by The Stefansson Library, New York, 1950, for St. Paul District, Corps of Engineers, U.S. Army, 26 p.

Laboratory experiments were performed to study elastic and plastic deformation of frozen ground at various temperatures. Based on these results, the author warned that the weight of buildings on sloping ground might be sufficient to cause plastic, glacier-like flow of frozen ground.

Tsytovich, N.A. (1950)
Principles of constructing and estimating the foundation of buildings erected on permafrost. Translated by A. Pressman, The Stefansson Library, New York, 1950, for St. Paul District, Corps of Engineers, U.S. Army, 17 p.

Section III describes "the influence of a construction on Permafrost". Observations of the visible results of construction on permafrost are given. Ground temperature measurements are made under two experimental buildings, one constructed on piles and the other with the foundation directly on the permafrost.

Tsytovich, N.A. (1960)
Bases and foundations on frozen soil: Highway Research Board Special Report 58, National Academy of Sciences - National Research Council, Publication 804, Washington, 93 p.

Chapter 5 is entitled "Properties of frozen soils on thawing". The significance of thawing is the loss in heaving strength of thawed permafrost. As water is forced out of the soils, the structure is lost, heaving strength is lost, and settlement occurs.

Tyrtikov, A.P. (1964)
Questions concerning the improvement of tree growth conditions in northwestern Siberia. Problems of the North. No. 7: 135-139.

Destruction of the soil cover and peat layer in sparsely eroded areas leads to a rise in the soil temperature (near the surface) and a thickening of the thawed layer (over several years). This leads to improved soil aeration increased microorganism action and a longer growing season, i.e.: general improvement in soil condition, which in turn produces better tree growth.

Watmore, T.G. (1969)
Thermal Erosion Problems in Pipelining. Proceedings of the Third Canadian Conference on Permafrost, 14 and 15 January, 1969, prepared by R.J.E. Brown. Technical Memorandum No. 96, N.R.C. Associate Committee on Geotechnical Research, Ottawa, pp. 142-162.

The paper gives a description of settling, erosion, and eventual renewed surface cover in areas along a test pipeline, bulldozed cutlines, and a surface fire. This is largely descriptive and does not indicate changes in engineering properties of permafrost upon thawing.

Wiggins, I.L. and Thomas, J.H. (1962)
A flora of the Alaskan arctic slope. Arctic Institute of North America, Special Publication No. 4: ix + 425 p. (University of Toronto Press.)

p. 14 Caribou (Rangifer arcticus), "particularly during the spring and autumn migrations, ... cut extensive trails over the foothills through passes, and toward convenient crossing places along the major streams and rivers. Severe local erosion can, and at many places, does occur where the caribou have broken the tundra sod on banks above streams or lakes. Their trails criss-cross the tundra and around many of the shallower ponds and lakes the trampling done by a herd of caribou destroys much vegetation. In some passes the surface is almost devoid of plant cover."

p. 28-31 Describes minor plant habitats such as camp sites, vehicle trails, shot holes and drained lakes.

APPENDIX B

SOME EFFECTS OF A FOREST FIRE ON THE PERMAFROST ACTIVE LAYER AT INUVIK N.W.T. [1]

J.A. Heginbottom

Geological Survey of Canada

From August 8, 1968, until some rain fell on August 18, a forest fire near Inuvik burned over a total area of more than 350 sq. km. In fighting the fire, some 40 km of fire-guard were constructed, mainly using bulldozers. A short review of the fire was produced by R.M. Hill (1969) and reports were filed by the Forest Management Officer (Taylor 1968). Ground conditions shortly after the fire were observed by Bliss (1970), Mackay (1970), and Watmore (1969).

Reports of the effect of forest fires on permafrost have been published by Cody (1964; 1965), Kriuchkov (1968), Lutz (1956), and Mackay (1963). This paper will concentrate on two aspects of the effects of fire on the active layer. The first is a description of detailed levelling of the ground surface and measurements of active layer thickness in the burned area. The second is a brief description of some earthflows in the valley of Boot Creek.

[1] Reprinted from:
R.J.E. Brown (editor), Proceedings of a Seminar on the Permafrost Active Layer, 4 and 5 May, 1971. Canada, NRC/ACGR Tech. Memo. No. 103: 31-36, December 1971.

DETAILED LEVELLING

In late-May, 1969, eight months after the fire, an experiment was begun to monitor changes in the elevation of the ground surface and changes in the annual depth of thaw of the ground resulting from the forest fire. The site chosen was astride the southern boundary of the burned area, about 3 km southeast of Inuvik. This area was chosen because of its proximity to a deep pipe bench mark installed by G.H. Johnston of the National Research Council of Canada. All the levelling has been tied into this bench mark which, for the purpose of the study, was given an arbitrary elevation of 100 m. Three lines, each 30.5 m long, were laid out in such a manner that they could be reoccupied from year to year. Two of the lines were laid out in the burned area: one in an area that had been burned but was otherwise undisturbed and the other along the centre of a bulldozed fire-guard. The third line was established about 500 m to the southeast in an area that was both unburned and undisturbed, and was set up as a control on the other two. As far as could be determined from ground inspections and examination of pre-fire photographs, the vegetation and site conditions of the two test lines were essentially the same as that presently existing along the control line.

The ground surface along all three lines consisted of hummocks, one to two metres across and separated by trenches 30-80 cm wide and about 35 cm deep. The hummocks were composed of a dense, sticky, grey-brown, silty clay with little or no profile development. In the unburned area this clay was covered with a thin layer (<5 cm) of humus, mosses and lichens. The trenches were underlain by organic material and peat. The vegetation of the control line comprised open growths of spruce, with a shrub layer of grasses, sedges, forbs, mosses and lichens. In the burned area all the vegetation was completely destroyed.

Survey Procedures and Analysis.

The original surveys were undertaken in the spring of 1969, between May 29 and June 6. The first resurvey was made at the end of the summer of 1969, on September 15 to 17. The second resurvey was made in mid-summer of 1970, on July 4 and 5. A series of levels was run from the bench mark to each line, and then the ground height was measured at 30 cm intervals along each line. At these same points the depth of the thawed ground was also determined with a pointed steel probe. The ground surface elevation was measured to the nearest millimetre, while the depth of thawed ground was recorded to the nearest half-centimetre. It is felt that the actual survey stations along each line were reoccupied during subsequent surveys with an error of less than 3 cm. The resulting data were plotted as a series of profiles showing the absolute elevation of the ground surface and of the base of the thawed ground. Profiles from the different survey dates were compared, and the differences noted and analysed. The different changes which occurred in the various areas examined were also noted and considered.

The survey data provided information on three parameters: (1) the absolute elevation of the ground surface, (2) the form or shape of the ground surface, and (3) the depth of thawed ground and, by inference, the thickness of the active layer. Each parameter was considered independently for each of the survey lines and the lines were then compared. The effects of burning on hummocks and on trenches was considered independently and, finally, an estimate was made of the ice content in the upper levels of the formerly frozen ground. The data will not be discussed in detail, and only a statement of the conclusions reached will be presented in this paper. Over the first summer there was a

general, minor decline in the absolute elevation of the test line of some 19 cm. This was coupled with a flattening of the microrelief as the hummocks became generally less pronounced. The other effect of burning has resulted in an increase in the depth of thawed ground. This did not manifest itself over the first summer, but by July 1970, the median depth of thawed ground in the burned area was 9 cm greater than that in the unburned area. This difference was maintained until the end of August 1970.

The effects of bulldozing were more obvious. Over the first summer there was a definite decline, which averaged 28 cm by September 1969, in the absolute surface elevation of the ground surface. There were no changes in the ground surface form, which was to be expected, since the original surface of hummocks and trenches was completely destroyed by the bulldozing. Again the main effect of the disturbance was to increase the depth of thaw. Over the first summer, the median depth of thaw was 22 cm greater in the bulldozed area than in the undisturbed control area, and by August 1970, this difference was over 35 cm, or an increase of 83%.

The proposed explanation for the difference in effect between burning and stripping is that burning alone does not remove all the insulation provided by the moss and peat layers at the ground surface. Certainly a considerable amount is removed, and the albedo of the surface is drastically lowered. However, sufficient peat, and even some dead moss, remains to retard the passage of summer heat into the ground as compared with the bare mineral soil surface of the bulldozed fire-guard.

Over the summer of 1969, the ground beneath the trenches in the burned area thawed about 15 cm deeper than beneath the trenches in the unburned area. However, during the same time period the depth of thawed ground was 9 cm greater under unburned hummocks than under burned hummocks. By late August 1970, this situation was reversed, with the thawed ground being 16 cm deeper under burned hummocks and only 7 cm deeper under burned trenches than under their unburned counterparts. At this time, no explanation of these observations is offered.

Finally, considering the median depth of thawing in relation to the decline of the ground surface resulting from both burning and bulldozing, estimates can be made of the ice content of the upper layers of the former frozen ground. In the burned test area, between late-May and mid-September 1969, the ground surface declined 19 cm whereas the median depth of thawed ground remained essentially the same at 42 cm. This was taken to mean that the equivalent of 19 cm of ice melted and drained away from the top 61 cm (42 + 19 cm) of ground. Thus 33% by volume of the upper 60 cm of ground profile was ice. For the bulldozed test area, between late-May and mid-September 1969, while the ground surface declined by 28 cm the median depth of thawed ground increased from 42 to 65 cm. Thus the top 93 cm (65 + 28 cm) of ground contained 28 cm of ice, also equivalent to 33% by volume of ice in the upper metre of ground.

EARTHFLOWS

Seventeen earthflows occurred along Boot Creek Valley in the burned area between May 22 and August 9, 1969. They are all located along the north side of the valley, and between one and three kilometres from 'Airport Road'. On May 22, a ground traverse up Boot Creek Valley showed no earthflows, either fresh or old, whereas new aerial photographs, taken on August 9, showed the flows to be fully developed. They were inspected on the ground on September 14, 1969.

Boot Creek Valley, in this section, runs from east-northeast to west southwest. It is asymmetric in cross-profile, with a steep north-facing slope (typically 14°) and a less-steep, south-facing slope (7° on the lower part and 11° on the upper part). All of the earthflows along the valley are on the south-facing slope, and all but three have their roots high up on the steepest part of the slope, where the slope angle is often between 12° and 13°. The debris lobes have run out onto the flatter, lower part of the valley side and several have run right to the edge of the creek itself. Each earthflow consists of three parts: a hopper at the top, a chute with a slickensided floor, and a debris tongue at the base. The overall length of the flows examined ranges from 200 to 500 m. The hoppers are generally about one metre deep and 12-15 m in diameter. The chutes are approximately one metre deep and 5 m wide. The chute floors, in September 1969, were slickensided and it appears that the slide plane, or chute floor, at the time of flowage coincided with the base of the thawed zone. Some 12 cm of thawing developed in the chute floors between the time of flowage and the inspection of the earthflows in September. The debris lobes had not only pushed over trees in their path but some had carried up to a score of birch trees (7-10 m tall) for distances of some 120 to 150 m downslope. In September the debris lobes, which were about one metre deep and 10-20 m wide, were far too liquid to walk on.

In April 1969, through the centre of the area of earthflows, two seismic lines were run: one along Boot Creek Valley and another across the valley 2.5 km east of 'Airport Road'. None of the earthflows owes its initiation to the presence of these seismic lines. Although several flows crossed a seismic line, the hoppers or root areas were all located on the higher ground above them, thus indicating that the seismic lines were not related to the development of the earthflows.

The earthflows are not unique to Boot Creek Valley, although they are quite well developed in this location. On the low level aerial photographs, a few smaller examples can be seen in some of the creek valleys to the north of Boot Creek and on the Caribou Hills. Many other examples have also been seen from the air, in recently-burned areas along the bluffs of the Arctic Red River and around the Sans Sault Rapids. Several areas of flows were observed on the bluffs of the Ramparts River and the Mackenzie River near their confluence, along the Donnelly River, and on the bluffs of the Mackenzie River south of East Mountain. All were in areas that were burned in extensive forest fires in 1969.

However, similar earthflows that are apparently not related to forest fires have been reported from the Ramparts River area (K. Hall, *personal communication*) and from the left bank of the Mackenzie River downstream from Norman Wells. The association of forest fires and active-layer earthflows thus remains to be demonstrated.

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APPENDIX C

ON THE THERMAL REGIME OF THE PERMAFROST ACTIVE LAYER AT INUVIK N.W.T.[1]

J.A. Heginbottom

Geological Survey of Canada

As part of a larger study on the effects of terrain disturbance on the stability of permafrost conditions, an attempt is being made to evaluate some of the changes which occur in the thermal regime of the permafrost active layer following surface disturbance. It is hoped that sufficient understanding of the processes involved can be acquired to enable a predictive model to be developed. This report is of a preliminary nature, and will describe the experimental set-up, discuss some of the early data acquired, and indicate the proposed course of development.

Many writers have noted that, in permafrost areas, the first effect of disturbance of the ground surface, unless rehabilitative measures are taken, is a marked thickening of the active layer (see for example: Brown, Rickard and Vietor, 1969; Heginbottom, 1971; Kallio and Rieger, 1969; Mackay, 1970; Watmore, 1969). The sequence of events in this process appears to be that damage to or removal of the vegetation on the surface peat layer permits increased heat penetration during summer, which leads to melting of more frozen ground than before disturbance and thus to a thicker active layer. The consequences of this thickening depend on the water content of the thawed ground, the macro-slope of the surface and the stability of the slope material. One consequence can be the initiation of active-layer earthflows (Heginbottom, 1971), river bank failures (Isaacs and Code, 1972) or other forms of slope failure (Hughes, 1972). Other instances of the effects of surface disturbance and degradation of permafrost are described by Brown (1970). The experiments to be described here are designed to examine this process in some detail.

THE ACTIVE LAYER

The active layer is the surface layer of soil or rock which is subject to annual freezing and thawing. Popular usage has tended to restrict the term to areas where the ground below the active layer is perennially frozen to some depth, and this usage will be maintained here. In the Inuvik area, the surface layer of the ground is a complex of mineral soil hummocks separated by shallow, moss-filled trenches. The hummocks are composed of a dense, sticky, grey-brown clay-silt showing little or no soil profile development. Some hummocks have mineral soil exposed at the surface, but most are covered with a thin layer (less than 5 cm) of humus, mosses and lichens. The hummocks are generally one to two metres across whereas the trenches between are 30 to 80 cm wide and about 35 cm deep. The trenches are moss-filled, and underlain by wedges of peat extending well below the base of the natural active layer.

1
Paper presented at Seminar on the Permafrost Thermal Regime, 2-3 May, 1972, Saskatoon, Saskatchewan.

Thus, the spatial structure of the active layer is very complex. Correspondingly, the thermal regime of the active layer is equally complex. The materials involved, namely mineral soil and peat, both frozen and thawed, have very different thermal properties, and the situation is further complicated by the latent heat of fusion involved in freezing or melting the water of the active layer, and by changes in the water content of the active layer. Following disturbance of the ground surface, the structure of the active layer is more or less severely changed. Probably the simplest situation is that resulting from deep bulldozing or stripping of the surface, such that all the vegetation and peat are removed. Shallow bulldozing or topsoil stripping leave the structure basically the same, but with less peat and little or no vegetation. Mechanical damage to the ground surface without removal of any material and forest fire result in more complex structure of the active layer. Following disturbance of the ground surface, the structure of the active layer is more or less severely changed. Probably the simplest situation is that resulting from deep bulldozing or stripping of the surface, such that all the vegetation and peat are removed. Shallow bulldozing or topsoil stripping leave the structure basically the same, but with less peat and little or no vegetation. Mechanical damage to the ground surface without removal of any material and forest fire result in more complex structure of the active layer.

A further consideration of the effect of surface disturbance on the active layer is the question of how far the effects spread beyond the boundary of the disturbance. The answer to this question has considerable interest for the design of structures and operations in the north. It is also of interest in the design of research experiments on the effects of surface disturbance.

THEORETICAL CONSIDERATIONS

The transport of heat in a porous medium such as soil normally involves the simultaneous operation of several different processes. Conduction is responsible for the flow of heat in the solid material while, across the pores, conduction, convection and radiation act in parallel. If water is present in the system, two additional processes must be included; the latent heat of distillation and the mass transfer water in response either to the temperature gradient or to some other force such as gravity.

In the past, calculations of temperature and heat flow in the soil have been made using models derived to describe heat conduction in homogenous, isotropic solids. The assumptions controlling the derivation of such models are not normally satisfied in a soil situation. The usual approach used to solve this problem is to select experimental conditions such that all mechanisms of heat transfer other than conduction may be neglected. This may be termed the "simple conduction" approach. This simplistic approach has been attacked (Nielsen and Biggar, 1967) and recent papers by Nakano and Brown (1971, 1972) have presented a model which appears capable of including the latent heat of fusion requirements for freezing or thawing the soil and changes in the thermal diffusivity of the soil with changes in temperature and moisture content.

THE EXPERIMENTS

In July 1971, twelve 2 m cables of thermistor beads were placed in shallow drill holes near Inuvik, N.W.T. Drilling was done in such a manner as to minimize thermal disturbance of the active layer. Of the twelve cables, two were placed in otherwise undisturbed mineral soil hummocks and two in the

intervening trenches. On each of these cables were seven thermistor beads, between 2 cm and 200 cm below the surface, and one bead set to measure air temperature. The objective of this set of cables is to consider the differences in some thermal properties between a hummock and a trench, and thus to consider the differences between essentially mineral soil and essentially organic soil.

The eight remaining cables had only four thermistor beads each, spaced between 25 cm and 200 cm below the surface. They were installed in two sets of four cables, spaced either side of the boundaries of two disturbed plots. These plots had been deliberately disturbed in March 1971 by bulldozing off approximately 10 cm of peat and mineral soil. The thermistor cables were placed 2 m and 5 m on either side of the boundaries between the bulldozed terrain of the plots and the adjacent undisturbed terrain. The object of these installations is to consider the effects of the surface disturbance and to investigate the boundary effects in the active layer resulting from this disturbance.

Temperature readings were taken on a weekly basis between mid-September and December, with readings in late January and February. In addition, two thermistor thermographs of the Canada Department of Agriculture pattern (Voissey et al., 1964) were used to make quasi-continuous readings (i.e.: approximately every half hour) from all the beads on one cable in a hummock and one cable in a trench.

PRELIMINARY RESULTS

This discussion is based on the temperatures recorded between mid-September 1971 and February 1972, and must be considered as preliminary in nature. The period covers the time of fall freezeback. The situation under a hummock and under a peat trench will be examined first. Figure 1 presents ground temperature isotherms (geotherms) for the period between August 1971 and February 1972 for Cable 10 and 11. Cable 10 is in a mineral soil land hummock, Cable 11 is in the peat beneath a trench. The solid lines show the 1C^{o} isotherms, the short dashed lines show selected 0.2C^{o} isotherms, and the long dashed lines indicate areas where the pattern is conjectural. Temperature data from a thermistor bead 5 cm above the ground surface guided the plotting of the geotherms right at the ground surface. The geotherms appear to cross the surface without any strong refractions. The heavily shaded part shows unfrozen ground whereas the lightly shaded areas show ground with a temperature between zero and -2C^{o}, and thus illustrate the "zero curtain" phenomenon (Muller, 1945). The short period of completely frozen ground under the hummock (Fig. 1a) on 3 October 1971 is quite anomalous. It does not appear under the trench or in the air temperature record, but it does appear in the data from Cable 9, (also in a hummock). It may be due to instrument error or it may be related to the heavy snowfall of 1-2 October. Figure 1 also shows that the unfrozen layer persisted until 6 November, although it had disappeared from under the trench by 15 October. The zero curtain period ended abruptly at all sites after 16 December when the winter temperature regime became firmly established.

It had been planned to use the data from the thermistor thermographs to estimate the thermal diffusivity of the ground under a hummock and under a trench. These results would then have been used to develop a prediction model for the disturbed sites. It had been hoped that, by calculating the thermal diffusivities from the penetration of diurnal temperature waves at successive dates in the fall, different values could be obtained for different ambient temperatures in

the ground. However the early, heavy snowfall of nearly 100 cm on October 1-2, just after the second thermograph had been started, prevented sufficient penetration of the diurnal temperature waves to such an extent that the thermal diffusivity of the ground material could not be calculated.

One estimate of the thermal diffusivity under a hummock was made using the data from the first thermograph for September 22-23. The model used a simple one, devised by Lettau (1966, p. 12). For the depth interval of 2-10 cm, and using Lettau's amplitude reduction model, a value of 2.93×10^{-3} cm^2 sec^{-1} was obtained for the thermal diffusivity. This value is of the right order of magnitude and is close to reported values of 2.3×10^{-3} for dry sand and dry clay (Van Wijk, 1963, p. 169) or 2.5×10^{-3} for dry soil (Terzaghi, 1952, p.11).

Concerning the cables in the disturbed areas, no attempt has been made to predict the pattern of isotherms which may be expected on the basis of observations of undisturbed hummocks and trenches and, at this time, only general comments will be made. Figure 2 shows the pattern of freeze-back of the active layer across the boundary of one of the bulldozed plots. The diagrams show the interpolated pattern of geotherms across the boundary for the dates given. In all cases the interpolations have been strictly linear. The conventions used in this figure are the same as those used in Figure 1; the bulldozed parts of the profiles are on the left.

To summarize the information on the effects of bulldozing which may be derived from these diagrams; in mid-September (Fig. 2a) the ground was warmer at all depths under the bulldozed area. The ground surface was definitely warmer, and the active layer was deeper by 45 cm. As the zero curtain became established in early October, the active layer remained generally warmer at all depths (Fig. 2b). However, by mid to late October, freeze-back from the surface was more advanced under the bulldozed area (Fig. 2c). This continued through mid-November (Fig. 2d) until, by mid-December (Fig. 2e), the only unfrozen area was just under the undisturbed area. Following the disappearance of the zero curtain period, heat loss was much greater from the undisturbed area--a reversal of the situation up to this time--and so, by late February, the pattern of geotherms is as shown in Figure 2f, with the ground again warmer at all depths under the bulldozed area, but the geotherms now sloping the other way.

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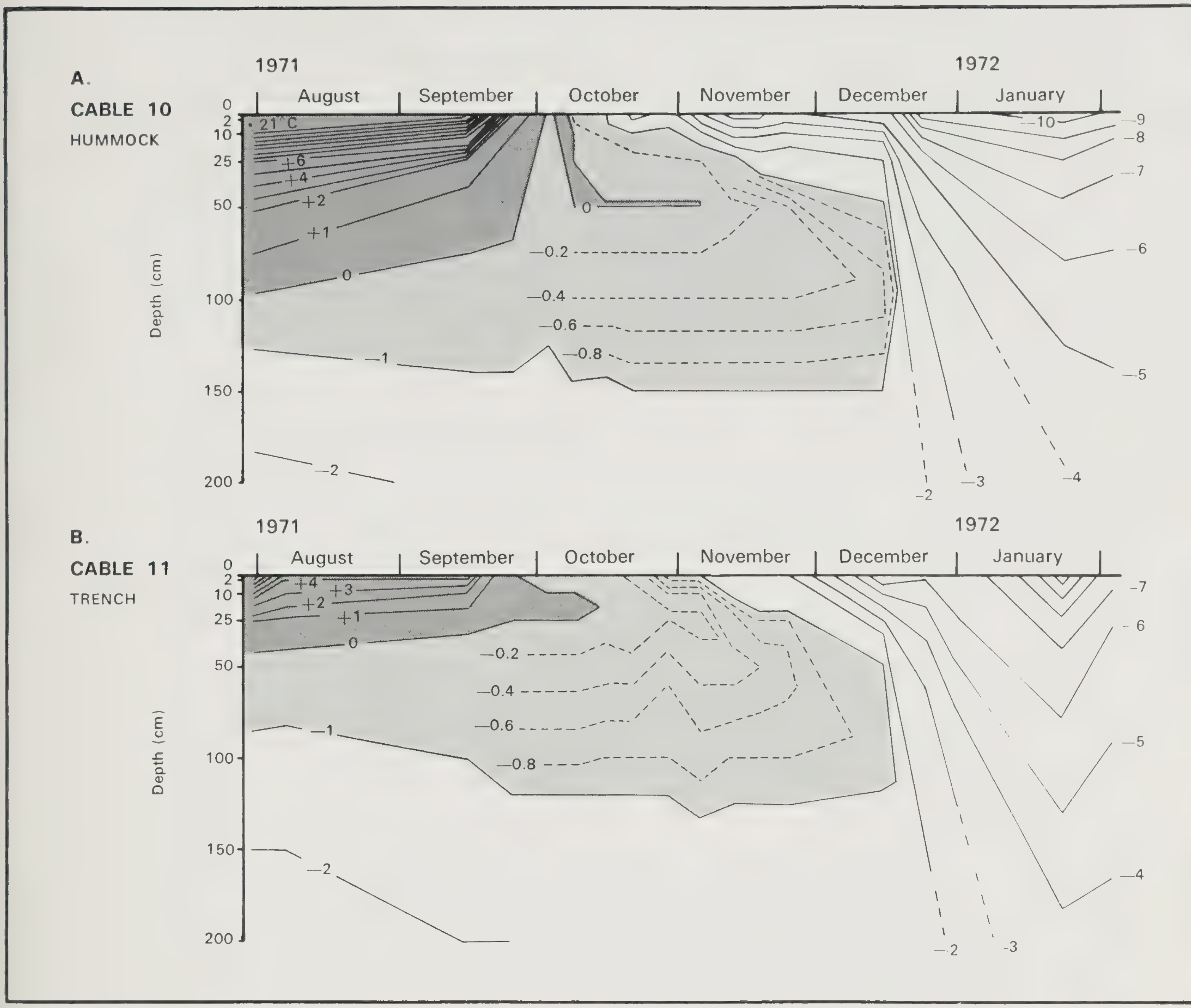

Figure 1: Geotherms for Cables 10 and 11 for the period August 1971 to February 1972.

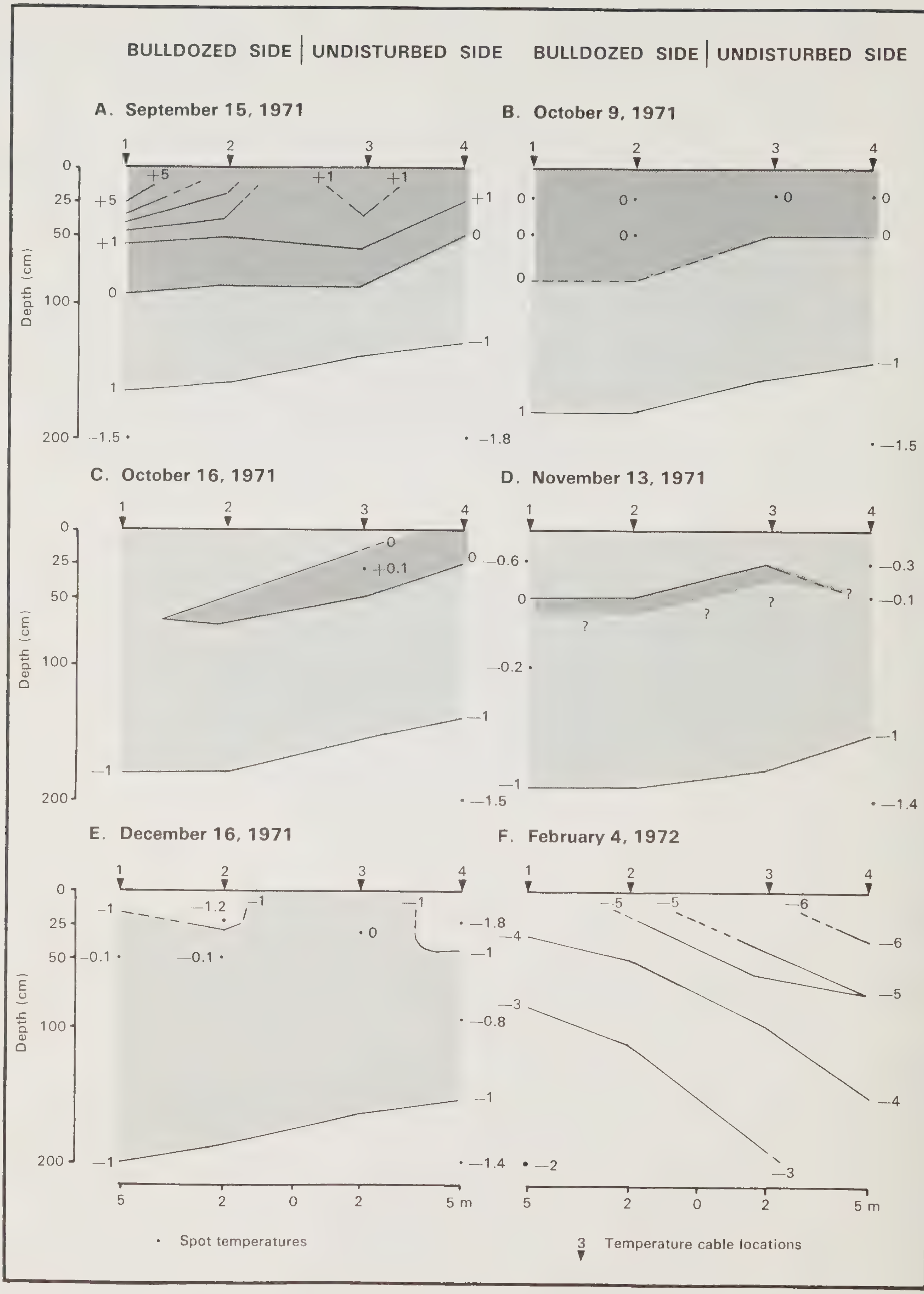

Figure 2: Geotherms illustrating the pattern of fall freezeback across the boundary of a disturbed area.